Newnes

ELECTRONICS EXPLAINED

Fundamentals for Engineers, Technicians, and Makers

Second Edition

Louis E. Frenzel Jr.

VISIT…

Electronics Explained

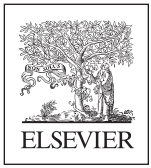
This page intentionally left blank

Electronics Explained

Fundamentals for Engineers, Technicians, and Makers

Second Edition

Louis E. Frenzel, Jr.
Austin, TX, United States



Newnes is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

Copyright © 2018 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices
Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-0-12-811641-8

For information on all Newnes publications visit our website at https://www.elsevier.com/books-and-journals

Publisher: Mara E. Conner
Acquisition Editor: Tim Pitts
Editorial Project Manager: Charlotte Kent
Production Project Manager: Mohanapriyan Rajendran
Designer: Mark Rogers

Typeset by TNQ Books and Journals

To Joan Ree with love for many happy years.

This page intentionally left blank

Contents

List of Figures xv
Preface to the Second Edition xxv
Preface xxvii

1. Learning About Electronics for Your Own Good 1

Introduction 1
It Is Not Like It Used to Be 2
What Is in It for You? 2
Electronics: The Big Picture 3
Communications 4
Computers 4
Control 4
Instrumentation 5
Components 5
How the Electronics Industry Works? 5
Electricity Versus Electronics 6
The Painful Truth 7
Cell Phone 8
Computers 9
Robots 11

2. Electronic Concepts: More Interesting Than You Think 15

Introduction 15
Electricity and Electronics 15
Atoms and Electrons 16
Charge, Voltage, and Current 16
Dynamic Electricity and Current Flow 18
Direction of Current Flow 19
Conductors, Insulators, and Semiconductors 20
Magnetism 20
Magnetic Fields 20
Electromagnetism 21
Electromagnetic Induction 23

Voltage Sources 24
Direct Current Voltages 24
Alternating Current Voltages 26
Practical Direct Current and Alternating Current Voltage Sources 29
Direct Current Voltage Sources 29
Fuel Cell 32
Alternating Current Voltage Sources 33
Analog and Digital Signals 34
Fourier Theory and the Frequency Domain 34

3. The Systems Versus Components View of Electronics 41

Introduction 41
Why Systems and Not Circuits? 41
Electronic Components 45
Switches 45
Resistors 45
Capacitors 47
Inductors 50
Transformers 51
Diodes 52
Transistors 52
Integrated Circuits 55

4. Electronic Circuits: Linear/Analog 63

Introduction 63
Linear Circuits 63
Amplifiers 64
Classifying Amplifiers 65
Amplifier Specifications 71
Filters 75
Oscillators 77
Mixers 78
Phase Detector 79
Phase-Locked Loops 80
Frequency Synthesizers 82
Power Supplies 84

5. Electronic Circuits: Digital 103

Introduction 103
Binary Numbers 103
Binary-to-Decimal Conversions 104
Using Hardware to Represent Binary Quantities 105
Decimal-to-Binary Conversions 105
Maximum Decimal Value for N Bits 106
BCD and ASCII 107
Parallel and Serial Data 112

Digital Logic Elements 114
Inverter 114
AND Gate 115
OR Gate 117
NAND and NOR Gates 117
Exclusive OR Gate 118
Flip-Flops 119
Storage Registers 120
Shift Registers 121
Counters 121
Common Logic Circuits 124
Multiplexer 124
Demultiplexer 124
Decoder 124
Comparators 125
Arithmetic Circuits 125
Digital Memories 126
Random Access Memory 126
Read-Only Memory 128
Programmable Logic Devices 129
Data Conversion 131
Analog-to-Digital Conversion 132
Digital-to-Analog Conversion 132
Resolution and Sampling Interval 133
Direct Digital Synthesis 134

6. How Microcomputers Work 139

Introduction 139
Concepts and Definitions 139
Computer Organization and Operation 142
Operational Details 145
Registers and the Arithmetic Logic Unit 145
Control Unit 147
Instruction-Word Formats 148
Program Execution Example 149
Microcomputer Buses 151
Popular Microcomputers 151
8- and 16-Bit Microcontrollers 152
32- and 64-Bit Processors 155
Digital Signal Processing 157

7. Radio/Wireless 159

Introduction 159
Radio Communication Systems 159
Three Basic Ways of Communications 160
Simplex 161
Half Duplex 161

Full Duplex 161
What Is a Radio Wave Anyway? 162
Electric and Magnetic Fields 162
Signal Speed 164
Signal Strength 164
Electromagnetic Frequency Spectrum 164
Radio Wave Propagation 168
Low and Medium Frequencies 168
High Frequencies 168
VHF, UHF, Microwaves and Millimeter Waves 169
Modulation 170
Amplitude Modulation 171
Sidebands 171
Bandwidth 172
Single Sideband Modulation 173
Frequency Modulation 173
Phase Modulation 174
Digital Modulation 174
Spread Spectrum 175
Orthogonal Frequency Division Multiplex 176
Radio Hardware 176
Transmitters 176
Receivers 177
Transceivers 179
ISM Band Transceiver 179
Antennas 181
Ground-Plane Antenna 181
Dipole 182
Yagi 182
Other Antennas 183
Transmission Lines 183
Microwave Antennas and Waveguides 185
Two-Way Radio 186
Aircraft 187
Citizens Band 187
Amateur Radio 188
Family Radio 188
Marine 188
Land Mobile Radio 189
Satellites 189
Radio Telescopes 191

8. Cell Phones 195

Introduction 195
Can You Hear Me Now? 195
The Cellular Concept 197
What Is Inside a Cell Phone? 199

What Type of Cell Phone Technology Do You Have? 200
Digital Modulation and Wireless Transmission Methods 203
Quadrature Amplitude Modulation 203
Orthogonal Frequency Division Multiplexing 204
Multiple Input Multiple Output 206
Spectral Efficiency 208
Access Methods and Duplexing 209
A Look Inside a 4G Cell Phone 212
The Latest Cell Phone Technology 213
Long-Term Evolution 213
Fifth-Generation Wireless Overview 214
Location Technology 216

9. Networking: Wired and Wireless 217

Introduction 217
Is Everything Networked? 217
Types of Networks 218
Wide Area Networks 218
Metropolitan Area Networks 218
Local Area Networks 218
Personal Area Networks 218
Home Area Networks 219
Storage Area Networks 219
Network Relationships 219
Network Interconnection Methods 219
Wired Networking Technologies 220
Types of Cables 221
Ethernet 223
How Is Ethernet Used? 225
Synchronous Optical Network 226
Optical Transport Network 228
How the Internet Works 228
Wireless Networks 230
Wi-Fi 231
Bluetooth 233
ZigBee 233
ISM-Band Radios 235
Radio Frequency Identification and Near-Field Communications 235
Broadband Technology 236
Cable TV Connectivity 237
Digital Subscriber Lines 237
Wireless Broadband 238
The Internet of Things 238
How Internet of Things Works 239
Wireless Technologies of Internet of Things and Machine 2 Machine 240
The Issues of Internet of Things 240

10. Audio Electronics 243

Introduction 243
The Nature of Sound 243
Microphones 244
Speakers 244
Digital Audio 245
Past Recording Media 246
Digitizing Sound 247
Digital Compression 248
How an MP3 Player Works 250
The Compact Disc 251
Audio–Video Receiver 254
Radio Choices 254
Surround Sound 256
Special Sound Applications 257
Wireless Speakers and Headphones 257
Downloading and Streaming Audio 257
Musical Instruments 257
Noise-Canceling Earphones 258
Sonar 259
Hearing Aids 259

11. Video Technology 261

Introduction 261
Video Fundamentals for the Impatient 261
Scanning Fundamentals 262
Aspect Ratio 262
Persistence of Vision 263
Analog TV 264
Digital TV 266
Color Video Principles 269
Video Compression 271
TV Transmission 272
TV Receiver 274
TV Screen Technology 274
Summary of Screen Technologies 277
3D TV 278
Cable Television 278
Satellite TV 283
Over-the-Top TV 285
Cell Phone TV 285
Closed-Circuit TV 286
Digital Video Discs 286
How a DVD Player Works 287
Blu-ray DVD 288
Virtual and Augmented Reality 288

12. Industrial Control 291

Introduction 291
Open- and Closed-Loop Control 291
Open-Loop Control 292
Closed-Loop Control 292
Controllers 294
Sensors 295
Temperature Sensors 296
Pressure Sensors 297
Switches 298
Potentiometers 298
Photoelectric Sensors 299
Flow Sensors 302
Output Devices 303
Relays 303
Solenoids 309
Motors 310
DC Motors 310
AC Motors 311
Other Actuators 312
Thyristors 312
Silicon-Controlled Rectifier 312
Diac 315
Triac 315
Programmable Logic Controllers 318
Organization 318
Operation 319
Programming 320
Data Acquisition Systems 321

13. Software, Programming and Electronics 325

Introduction 325
Software Fundamentals 325
Programming Languages 327
Programming 329
Developing Software for Embedded Controllers 334
Microcontroller Unit Interfacing 336
Platforms for Learning Programming 339
Parallax BASIC Stamp 2 339
PICAXE 339
Arduino 340
LaunchPad 341
Advanced Alternatives 341
Learning Programming 342
Books 342
Learn by Example 343

Online Tutorials 343
Online College Courses 343
Apply What You Learn 343

14. Soldering 347

Introduction 347
What is Solder? 347
Soldering Tools 348
Soldering Procedures 349
Desoldering 351

Appendix A: Book References 355
Appendix B: Projects Parts List 357
Appendix C: Learning Resources 363
Index 365

List of Figures

Figure 1.1	Major sectors of the electronics industry and common applications	04
Figure 1.2	General block diagram of how the electronics industry works from raw materials to end users	06
FIgure 1.3	Model of how all electronic circuits and equipment work. Input signals are processed by circuits and equipment into new output signals	08
Figure 1.4	Model showing how a cell phone communicates with a cell site to make a call	08
Figure 1.5	Block diagram representing any digital computer, be it a mainframe, PC, or embedded controller	10
Figure 1.6	The most common form of robot emulates a human arm and hand to perform work automatically under the control of a computer	12
Figure 2.1	Physics model of what a copper atom looks like	17
Figure 2.2	Basic electrical circuit used to describe every electronic circuit	19
Figure 2.3	Permanent bar magnet illustrating the magnetic lines of flux that surround it	21
Figure 2.4	(A) Current in a wire produces a magnetic field around it. (B) Coiling the wire increases the strength of the magnetic field	22
Figure 2.5	Relative motion between a magnetic field and a conductor such as a wire causes a voltage to be induced into the wire making it a voltage source	23
Figure 2.6	DC voltages. (A) DC voltage source such as a battery or power supply. One side is usually grounded to serve as a reference. (B) Fixed, continuous positive DC voltage shown over time. (C) Negative DC voltage. (D) Varying positive DC voltage. (E) DC voltage pulses	25
Figure 2.7	AC voltages. (A) AC voltage source drawn as a circle with a wave inside. The output polarity changes periodically. (B) Sine wave, the most common AC voltage shape. (C) Rectangular wave or AC pulses. (D) Triangular wave. (E) Random AC wave that may represent voice or video	27
Figure 2.8	Basic concept of any battery	29
Figure 2.9	Battery and cell symbols used in circuit diagrams. (A) Cell. (B) Four cells in series making a battery. Cell voltage add-up. (C) Symbol for battery of any number of cells. (D) Cells in parallel to increase current capability	31
Figure 2.10	Panel comprised of solar cells in series and parallel make up DC source that charges the battery in a spacecraft	32
Figure 2.11	Frequency-domain views. (A) 1-MHz sine wave. (B) 1-MHz square wave	35
Figure 2.12	A low cost digital multimeter that measures DC and AC voltages, current, and resistance	36

Figure 2.13 A simple solar power system 38
Figure 2.14 An experimental solar power system. The solar panel feeds the charge controller below the panel. The charge controller connects to and charges the black battery on the right. The other charge controller output connects to the inverter below. The lamp plugs into the inverter. Clip leads are used to make the temporary connections 39
Figure 3.1 Hierarchy of electronics from systems to components 43
Figure 3.2 System block diagram of typical personal computer 44
Figure 3.3 System block diagram of iPod or MP3 music player 44
Figure 3.4 Switch and how it is used 46
Figure 3.5 Types of resistors and schematic symbol 47
Figure 3.6 Standard resistor color code 48
Figure 3.7 Voltage divider, the most common resistor circuit 48
Figure 3.8 Capacitor construction and schematic symbol 49
Figure 3.9 (A) Charging capacitor, (B) discharging capacitor 49
FigurE 3.10 Low-pass filter, a common capacitor use 50
Figure 3.11 How capacitor passes AC sine wave but blocks DC voltage 51
Figure 3.12 Schematic symbol for inductor 51
Figure 3.13 Schematic symbol for transformer 51
Figure 3.14 Diode, its schematic symbol, and how to bias it for conduction or cutoff 52
Figure 3.15 How a diode rectifies AC into DC 53
Figure 3.16 Schematic symbol for bipolar junction transistor (BJT) and its inputs and outputs 53
Figure 3.17 Schematic symbol for MOSFET and its input and outputs 54
Figure 3.18 Simple BJT amplifier and how it works 54
Figure 3.19 Simple MOSFET switch and how it works 55
Figure 3.20 Typical integrated circuit today. This one is a dual-satellite TV tuner for set-top boxes. The size is only 7 × 7 mm. The pins are soldered to a printed circuit board 56
Figure 3.21 Common breadboarding socket for building prototypes or just experimenting 57
Figure 3.22 Soldering wires on the battery clip so they will plug into the breadboarding socket 58
Figure 3.23 Measuring battery voltage with multimeter 58
Figure 3.24 This is the circuit used to light an LED and how to wire it on the breadboard 59
Figure 3.25 Circuits for charging and discharging capacitor and respective wiring 60
Figure 3.26 Circuit that turns an LED off and on with MOSFET and wiring 61
Figure 4.1 Linear circuit has a straight-line response. As input varies, output varies by factor of 10 larger, producing straight-line output 64
Figure 4.2 Block symbol for amplifier. Gain, A, is often given. DC power inputs are not usually shown 65
Figure 4.3 Single-ended (A) and differential input (B) amplifiers. Inputs and outputs are referenced to ground 66
Figure 4.4 Class A amplifier conducts continuously 67
Figure 4.5 Class B amplifier conducts half the time, making it more efficient 67
Figure 4.6 Class C amplifier only conducts for part of a half cycle, but the current pulse stimulates resonant tank circuit that oscillates at desired frequency 68
Figure 4.7 Class D amplifier uses pulse width modulation (PWM) at higher frequency to switch higher voltages for greater output. Class D amplifiers are more efficient than any other type, and thus do not produce as much heat 69

Figure 4.8 Most commonly used operational amplifier circuit configurations. (A) Inverting amplifier, (B) noninverting amplifier, (C) follower, and (D) differential amplifier 70
Figure 4.9 Instrumentation amplifier widely used to amplify small sensor signals in industrial applications 71
Figure 4.10 Amplifier input impedance (A) and output impedance (B) 72
Figure 4.11 When one amplifier feeds another, input and output impedances form a voltage divider that attenuates the signal and offsets some of the gain 73
Figure 4.12 Cascading amplifier provides more gain. Total gain is product of individual gains or sum of decibel (dB) gains 73
Figure 4.13 Frequency-response curves show output versus input frequency. Curve in (A) is response of operational amplifier that extends from DC to 5-MHz cutoff frequency. Curve in (B) is response of common stereo audio amplifier 75
Figure 4.14 Four common filter types and their response curves and symbols. (A) Low-pass, (B) high-pass, (C) band-pass, and (D) band-reject or notch 76
Figure 4.15 Types of oscillators and their symbols. (A) Sine wave, (B) rectangular pulse, (C) voltage-controlled oscillator, and (D) crystal clock oscillator 77
Figure 4.16 Linear mixing with resistors (A) or an operational amplifier summer (B) 79
Figure 4.17 Nonlinear mixer used to generate higher and low frequencies 79
Figure 4.18 Phase detector converts phase shift into proportional DC average 80
Figure 4.19 Phase-locked loop 81
Figure 4.20 Frequency synthesizer using phase-locked loop. Changing the divider ratio changes the frequency 83
Figure 4.21 Typical power supply configuration using bus architecture, regulators, and DC–DC converters to get desired number of outputs 85
Figure 4.22 Concept of duty cycle and how varying pulse widths can be filtered into a proportional DC average voltage 86
Figure 4.23 Common DC-to-AC solar power system 88
Figure 4.24 The Velleman PCSU1000 oscilloscope. It has dual channels for observing two signals at once and a bandwidth of 60 MHz 89
Figure 4.25 Virtual instrument units. Left: National Instruments' myDAQ, Right: Digilent Analog Discovery 2 90
Figure 4.26 An AC–AC wall adapter transformer and a pot form a variable 60 (50) Hz signal source 92
Figure 4.27 A 555 timer IC circuit that generates rectangular waves 92
Figure 4.28 One type of breadboarding socket. Not all sockets have the A and B power and ground buses in which case you can designate any one group of 5 pins to power and another for ground 93
Figure 4.29 A 60-Hz sine wave displayed on an oscilloscope 94
Figure 4.30 The output of the 555 timer circuit displayed on an oscilloscope 96
Figure 4.31 The 555 IC connected as an audio tone generator with speaker 97
Figure 4.32 The 555 IC connected to flash an LED off and on 97
Figure 4.33 A half wave rectifier and regulated 5-V power supply 98

Figure 4.34 The half sine pulses as seen on the oscilloscope 99
Figure 4.35 Operational amplifier inverter circuit showing power supply detail 100
Figure 4.36 Operational amplifier noninverting amplifier circuit 101
Figure 5.1 Binary signal that represents 0 and 1 as voltage levels 104
Figure 5.2 Off/on switches are used to enter binary data into digital circuits 105
Figure 5.3 How lights or LEDs are used to represent binary data 106
Figure 5.4 Parallel binary data transfer over bus 112
Figure 5.5 Serial data transfer where 1 bit occurs after another in time 113
Figure 5.6 Logic symbols for inverter and truth table 114
Figure 5.7 Logic symbols for AND gate and truth table 115
Figure 5.8 How AND gate is used to turn signal off or on. (A) The AND gate showing the input and output names. (B) The waveforms of the inputs and output 116
Figure 5.9 Logic symbols for OR gate and truth table 117
Figure 5.10 Logic symbols for NAND gate and truth table 118
Figure 5.11 Logic symbols for NOR gate and truth table 118
Figure 5.12 Logic symbols for XOR and XNOR gates and truth tables 119
Figure 5.13 Logic symbols for flip-flops. (A) RS. (B) D type. (C) JK 119
Figure 5.14 Toggling T input on JK flip-flop causes it to change states, producing frequency division by 2 120
Figure 5.15 Cascading JK flip-flops produce higher-frequency division ratios, which is also a binary counter that counts from 0000 to 1111 120
Figure 5.16 Storage register from one word consists of FFs. It also has clock/load and clear/reset inputs 121
Figure 5.17 (A) Shifting serial data into shift register. (B) Shifting serial data out of shift register 122
Figure 5.18 Shift registers used for (A) serial-to-parallel data conversion and (B) parallel-to-serial data conversion 123
Figure 5.19 Counter storing binary value equal to number of input pulses that occurred 123
Figure 5.20 Digital multiplexer (mux) that selects one of four inputs to appear at the single output 124
Figure 5.21 Decoders. (A) 1-AND gate decoder that identifies input 0110. (B) 4-to-16 decoder that identifies 1 of 16 different 4-bit input values 125
Figure 5.22 Basic concept for random access memory (RAM). Address selects one of eight storage locations. Then data may be read from that location or data stored in it 126
Figure 5.23 RAM storage cells. (A) RS FF for SRAM. (B) Capacitor cell for DRAM 127
Figure 5.24 Storage cell used in EEPROM and flash memories is MOSFET with a special floating gate that keeps transistor off or on 128
Figure 5.25 PLD concept. (A) Block concept of programmable AND and OR gate arrays. (B) Simple circuit of PLD showing programming by dots on AND and OR gate arrays 130
Figure 5.26 Analog-to-digital conversion is performed by sampling analog signal at equal intervals and generating proportional binary value 132
Figure 5.27 Symbol for ADC with both parallel and serial output examples 133
Figure 5.28 Converting binary data back into analog signal with DAC 133
Figure 5.29 DAC output is stepped approximation to original analog signal 134
Figure 5.30 A generic block diagram of a direct digital synthesizer (DDS) 135
Figure 5.31 Pin out details of the 74HC00 quad NAND logic IC, a NAND test circuit with LED output, and a truth table 136
Figure 5.32 The output of a 555 timer is the input to a NAND gate 137
Figure 5.33 A 74HC161 IC binary counter clocked by a 555 timer to demonstrate the binary count sequence on LEDs 138

Figure 6.1	How a microcomputer controls external devices	141
Figure 6.2	How a microcomputer monitors external devices	141
Figure 6.3	Controlling liquid level in a tank automatically with a microcomputer	142
Figure 6.4	General block diagram of any digital computer or microcontroller	143
Figure 6.5	How data is manipulated in a register. Examples of shifting data, incrementing and decrementing a register, and clearing (resetting) a register to 0	145
Figure 6.6	How ALU adds or otherwise processes two data values	146
Figure 6.7	Program counter identifies the address in memory to be accessed	147
Figure 6.8	Three common instruction-word formats with addresses or data	149
Figure 6.9	Example of program stored in RAM for execution using various CPU registers	150
Figure 6.10	Only one source may transmit at a time on a bus. Others are disconnected. All destinations can receive the transmitted data	152
Figure 6.11	General block diagram of 8051 microcontroller. It is very similar to most other controllers in terms of major circuits and their interconnections	153
Figure 6.12	ASCII letter "j" being sent over an RS-232 interface using a UART	156
Figure 6.13	Basic makeup of digital signal processor and its ADC and DAC I/O	157
Figure 7.1	Model of electronic communications system	160
Figure 7.2	Ways of communicating. (A) Simplex—one way and (B) duplex—two way: half—alternating send/receive and full—simultaneous send/receive	161
Figure 7.3	How an antenna creates a radio wave. (A) Antenna produces both electric and magnetic fields. (B) The electric and magnetic field lines are at a right angle to one another and to the direction of radiation	163
Figure 7.4	Electromagnetic frequency spectrum	165
Figure 7.5	Radio propagation of shortwaves	169
Figure 7.6	Line-of-sight (LOS) communications at VHF, UHF, and microwave	170
Figure 7.7	Amplitude modulation	171
Figure 7.8	Sidebands and bandwidth	172
Figure 7.9	Frequency modulation	173
Figure 7.10	Types of digital modulation. (A) ASK. (B) OOK. (C) FSK. (D) BPSK	175
Figure 7.11	Radio transmitter	177
Figure 7.12	Superheterodyne receiver	178
Figure 7.13	Single-chip UHF transceiver for low-speed, short-range digital data transmissions	180
Figure 7.14	Quarter-wave ground-plane antenna	182
Figure 7.15	Dipole antenna. (A) Dipole and (B) horizontal radiation pattern	183
Figure 7.16	Yagi antenna. (A) Yagi and (B) radiation pattern	184
Figure 7.17	Printed circuit board (PCB) patch antenna	184
Figure 7.18	Coaxial cable transmission line	185
Figure 7.19	Microwave horn antenna fed by waveguide transmission line	185
Figure 7.20	How a parabolic dish works. (A) Parabolic dish with horn, (B) transmission, and (C) reception	186
Figure 7.21	Concept of communications satellite	189
Figure 7.22	Satellite transponder	190
Figure 7.23	Wiring details for the ISM band short-range radio experiment	194
Figure 8.1	(A) Cell coverage of a given area. (B) Cell area covered depends on antenna pattern and environment	198
Figure 8.2	How small and large cells cover an area	198
Figure 8.3	Cell phone basic operations	200
Figure 8.4	Block diagram of basic cell phone	201

Figure 8.5 How QPSK is generated using mixers and a local oscillator shifted 90 degrees to produce in-phase (I) and quadrature (Q) signals that are summed 203
Figure 8.6 QPSK diagrams. (A) Phasor. (B) Constellation 204
Figure 8.7 How 16-QAM is generated and resulting constellation diagram 205
Figure 8.8 OFDM divides a channel into many subchannels or subcarriers, each of which is modulated by part of digital data to be transmitted 205
Figure 8.9 Generating OFDM is done by DSP and I/Q modulation 206
Figure 8.10 MIMO in a 4 × 4 configuration quadruples the data rate in an existing channel, while reducing the ill effects of multipath fading 207
Figure 8.11 The concept of MU-MIMO using beamsteering with a patch-type phased array antenna 208
Figure 8.12 Frequency division multiple access and frequency duplexing use two separate bands of frequencies divided into individual channels 210
Figure 8.13 TDMA multiplexing divides a channel into sequential time slots for the digital data 210
Figure 8.14 How CDMA is generated 211
Figure 8.15 A block diagram of 4G cell phone with multiple radios and functions 212
Figure 9.1 How LANs, MANs, and WANs connect to form a huge worldwide network of computers and other devices 220
Figure 9.2 Three main networking topologies—star, ring, and bus. Bus is the most widely used 221
Figure 9.3 Coax cable. It is now mainly used in cable TV networks. The most common is RG-6/U and uses F-type or BNC connectors 222
Figure 9.4 Twisted-pair cable. Initially used for telephones and is still used. Computer network cables use four twisted pairs. A shielded version is available where noise is a problem 222
Figure 9.5 Fiber optic cable. It is nonconductive because it is made of plastic and glass, and is used to transmit data as infrared (IR) light pulses 223
Figure 9.6 How binary data is transmitted over fiber optic cable 224
Figure 9.7 Ethernet hub or switch implements a bus that is accessed by RJ-45 connectors and twisted-pair cable 225
Figure 9.8 Ethernet frame or packet 225
Figure 9.9 A T-1 data frame commonly used in digital telephone systems as well as data interconnections in networks 227
Figure 9.10 Internet illustrated as cloud of fiber backbone connections through network access points (NAPs) that attach to WANs, MANs, and LANs 228
Figure 9.11 Protocols used in Internet. (A) Transmission control protocol (TCP). (B) Internet protocol (IP). The data in each frame are transmitted from left to right and top to bottom 230
Figure 9.12 Summary of short-range wireless networking technologies shown as data rate versus range 231
Figure 9.13 How a Wi-Fi access point or hot spot works 232
Figure 9.14 A mesh network can extend the overall range of a node and provide greater reliability through multiple possible paths. Most wireless mesh networks are ZigBee, but other wireless technologies may be used (e.g., Wi-Fi) 234
Figure 9.15 How RFID works. The tag has no power of its own but gets power from the transmitter in the reader 236
Figure 9.16 How the Internet of Things systems works 240
Figure 10.1 Cross section of speaker showing major components and how it works 244
Figure 10.2 Cross over networks keep signals of different frequencies separate for appropriate speakers 245

Figure 10.3 How audio signal is digitized. In this example, each sample is assigned a 4-bit code. The stepped approximation shown is what a DAC would deliver to the speakers 248
Figure 10.4 Voice signals up to 4 kHz for the telephone are sampled at an 8-kHz rate, producing an 8-bit sample, each 125 μs. Stringing the samples together in a serial data stream produces a digital signal at a 64-kHz rate 249
Figure 10.5 General block diagram of a digital music player like Zune MP3 or Apple iPod 250
Figure 10.6 Digital music on a CD is encoded as pits and lands on the CD surface. These are burned in by a laser. A laser light shined on the pits and lands produces a reflection that a photo-detector picks up to create the original digital data 252
Figure 10.7 Block diagram of CD player 253
Figure 10.8 Block diagram of typical audio–video receiver, the heart of the audio reproduction part of a consumer home entertainment center 255
Figure 10.9 How 5.1 surround-sound system is set up 256
Figure 11.1 How scanning converts a scene of light and color into an electronic signal 263
Figure 11.2 TV screen size and aspect ratio 264
Figure 11.3 Interlaced scanning helps reduce flicker. Sync pulses help keep the receiver and transmitter in step with one another 265
Figure 11.4 Digital TV is created by digitizing the analog video signals with an ADC, and then converting it into a serial bitstream of video data words 267
Figure 11.5 TV screens can be thought of as thousands of rows and columns of pixels, each represented by data 267
Figure 11.6 Any color of light can be reproduced by mixing red, green, and blue light in the right proportion 269
Figure 11.7 Red, green, and blue digital color signals are generated by filtering the scene into its red, green, and blue components, and then digitizing the resulting analog signals 270
Figure 11.8 HDTV packet for ATSC US digital color TV system 272
Figure 11.9 General block diagram of TV transmitter 272
Figure 11.10 US ATSC system translates the digital bitstream into an eight-level signal to transmit multiple bits per level, making higher data rates in a given bandwidth possible 273
Figure 11.11 Simplified block diagram of digital TV set 275
Figure 11.12 Inputs and outputs of modern digital TV set 276
Figure 11.13 How color pixels are formed on a TV screen. Pixel format typical of LCD or LED screens 277
Figure 11.14 Coax cable bandwidth up to 1 GHz can contain about 130 6-MHz channels 279
Figure 11.15 General block diagram of modern cable TV system 280
Figure 11.16 Simplified block diagram of modern cable box with DVR 282
Figure 11.17 TV distribution satellites in geosynchronous orbits act as wireless relay stations 283
Figure 11.18 Video from all sources is transmitted uplink to satellite that rebroadcasts it back to Earth over downlink to home receivers 284
Figure 11.19 Satellite TV home system consists of antenna with low-noise block converter, receiver, and TV set 284
Figure 11.20 Simplified block diagram of satellite TV receiver 285
Figure 11.21 Block diagram of standard DVD player 287
Figure 12.1 General block diagram of industrial control process 292
Figure 12.2 Open-loop control system for filling vat with liquid via a pump 292
Figure 12.3 Generic diagram of any closed-loop control system with feedback 293

Figure 12.4 Filling vat with liquid automatically with closed-loop control system 294
Figure 12.5 Closed-loop control system for motor speed control and regulation 295
Figure 12.6 Most resistive sensors such as an RTD or thermistor are placed in a bridge circuit to condition them to provide amplified output voltage 296
Figure 12.7 Characteristic curve of thermistor and simple voltage divider circuit producing output voltage 297
Figure 12.8 Strain gauge is a resistive element whose value changes with stress or pressure 298
Figure 12.9 Schematic symbols for photo cells. (A) Photoconductive or photoresistive, (B) photovoltaic or solar cell, and (C) photo transistor 299
Figure 12.10 Photodiode and its simple output circuit 300
Figure 12.11 Simple off/on photo control circuit. Light turns on automatically at dark and off when light is present 301
Figure 12.12 Simple tachometer circuit using phototransistor to create pulses that are averaged into a DC voltage proportional to speed 302
Figure 12.13 Cross-sectional view of typical relay showing major components and schematic diagram 303
Figure 12.14 Common relay contacts. (A) Form A, (B) form B, and (C) form C 304
Figure 12.15 Reed relay 305
Figure 12.16 Controlling a large current with a smaller current with a relay 306
Figure 12.17 Latching a relay with its own contacts 308
Figure 12.18 Operating a relay with a transistor is a common application. The diode protects the transistor when power is removed from the relay coil 308
Figure 12.19 A solenoid produces linear motion using magnetic principles 309
Figure 12.20 Using an H-bridge circuit to reverse the current flow and direction of rotation in a DC motor 311
Figure 12.21 Schematic symbol of an SCR 313
Figure 12.22 Circuit that shows how an SCR is turned on and off 313
Figure 12.23 Using an SCR to control power to a load using AC. The SCR rectifies the AC 314
Figure 12.24 Schematic symbol for triac 315
Figure 12.25 Equivalent circuit of triac shown with SCRs 316
Figure 12.26 Lamp dimmer circuit using RC phase shifter and diac to control current in the load 316
Figure 12.27 AC waveforms in a lamp load controlled by a triac. (A) Waveforms with triggering at 60 degrees, (B) waveforms with triggering at 120 degrees. The longer pulses produce higher average current in the load 317
Figure 12.28 General block diagram of PLC 318
Figure 12.29 PLC operational scan cycle 319
Figure 12.30 Sample ladder diagram and PLC application program 321
Figure 12.31 The key components and organization of a typical data acquisition system 322
Figure 12.32 A simple feedback control circuit for temperature control 323
Figure 13.1 Flowchart symbols 330
Figure 13.2 A flowchart illustrating a computer program 331
Figure 13.3 Structured programming divides a problem into smaller and smaller submodules 332
Figure 13.4 Block diagram of the complete microcontroller software development process 335
Figure 13.5 Driving an LED directly from the MCU output 336
Figure 13.6 An NPN driver transistor for higher loads 337
Figure 13.7 An N-channel enhancement mode MOSFET driving a DC motor 338
Figure 13.8 Using a pushbutton switch to generate an input logic level 338
Figure 13.9 A comparator and thermistor used for temperature sensing 338

Figure 13.10 The Parallax BASIC Stamp Activity Kit experimental board is designed to be operated from a 9-V battery. The PIC MCU is the IC above the reset button in the center 340
Figure 13.11 The Arduino Uno R3 is one of the most widely used microcontroller learning platforms 341
Figure 13.12 The Texas Instruments' LaunchPad development board uses an MPS430 microcontroller 342
Figure 14.1 A common soldering iron used in electronic work 348
Figure 14.2 Tools used in soldering. On the left is a wire stripper. Next is a pair of needle-nose pliers. On the right is a side cutter for wire 349
Figure 14.3 Soldering two wires together. Apply solder to the heated wires not to the iron tip 350
Figure 14.4 Soldering components to a printed circuit board 350
Figure 14.5 Soldering a surface mount part to a PCB 351
Figure 14.6 Tools for desoldering, a solder sucker and solder wick 352

This page intentionally left blank

Preface to the Second Edition

This revised and enhanced edition of *Electronics Explained* is still written for those of you who want to learn about electronics in the shortest amount of time. The original goals of the book as outlined in the Preface below are the same, but now the book has been expanded and updated to match the latest developments in electronics. This revised version also hopes to make you more of a hands-on electronic experimenter, hobbyist, DIYer, or maker. The highlights of the new edition are as follows:

- All chapters are revised to include any new developments, technologies, and products. Some of the new topics covered include 4K high-definition video, virtual reality, the latest wireless standards, the Internet of things, and the latest 4G and 5G cellular technologies.
- Increased number of hands-on projects with electronic components and test equipment. Virtual instruments are introduced and a wide range of analog and digital projects and experiments are provided.
- A new chapter on soldering, a core skill of any electronic person. Building a kit is a recommended project.
- A new chapter on programming and interfacing embedded controllers. It is difficult to be an electronics enthusiast today without knowledge of microcontrollers and how to program them. Modules like the Arduino are described and examples of programming using BASIC and C languages are included.

Happy learning and experimenting

Lou Frenzel
2017

This page intentionally left blank

Preface

This book is for those of you who want to learn about electronics and computers but frankly are put off by all the gory details. If you have a short attention span, a nonexistent background in science, math, and technology, and are looking for near-instant gratification of electronics knowledge, this book is for you. Electronics is a complex subject, especially if you want to be an electronics engineer. However, if you are merely curious or just need a working knowledge of electronics for your job, this book will give you a basic education on the fundamentals without boring you to death or loading you down with the excruciating details that other books lay on you. What I have attempted to do is write a book that tells you the most important concepts and fundamentals but leaves out the minutiae that only an engineer will need or appreciate. This book contains exactly what you need to know today in the 21st century.

There are lots of basic electronics books around, and you may already have read some. This one is really different. First, it does not go into detailed circuit analysis. Why? Simply, all electronic equipment today is made up of integrated circuits or chips, and we cannot see the circuits, access them, or even repair them. If you are an electronic engineer designing integrated circuits, yes, you do need to understand their operation. If you just want to learn how electronic equipment works, then you can skip this detail. This book treats circuits as simple functional building blocks whose purpose and application are easily understood.

Second, this book presents what I call the *new* electronics. Most basic electronic books dwell on the older components and circuits and ignore how electronics really is today. These books do a good job teaching you the history of electronics but little else. What you will see in this book is a fresh new way to look at and understand electronics, especially in the context of the familiar applications you use every day made with the most advanced integrated circuits. If you complete this book and still want more, one of the more traditional basic electronics books would be your next step. See the appendix for my recommendations.

The first three chapters introduce you to the electrical principles that form the basis of electronics. You will learn the core concept of electronics, which boils down to how to generate current flow and then control it to do something useful. Magnetic fields are also covered, since magnetism is just as important in electronics as current flow. But do not worry, even if you never took a physics course you can easily get through this material.

Next, you learn about the basic components of electronics such as resistors, capacitors, inductors, transformers, diodes, transistors, and especially integrated circuits. Then you will discover all the different types of electronic circuits used to make up any electronic device. The functional block diagram approach is used here so that you will not have to do the nitty-gritty circuit analysis that has you chasing electrons through components and solving simultaneous equations.

An important part of this book is the coverage of computers, and specifically of embedded controllers, that is, those tiny single-chip microcomputers or microcontrollers that are built virtually into every electronic device. Digital signal processors are also covered since they also appear in most modern electronic equipment. You cannot name an electronic product today that does not have one of these embedded computers in it. You really need to know what these are and how they work, as they are the very heart of electronic devices today. Programming and interfacing are included with C and BASIC language examples.

The rest of the book consists of descriptions of how all the major electronic products and systems work. The entire range of modern electronics is covered, including major things like cell phones (LTE and 5G), video (cable, HDTV, 4K, DVD, VR, OTT, etc.), audio (stereo, CDs, MP3, streaming, etc.), satellites (GPS, TV, radio, etc.), radio (broadcast, marine-aircraft-shortwave, ham, CB, family radio, etc.), and everything else you can think of. And it is all explained using basic building blocks rather than detailed circuits.

Finally, if you want involvement as you read the book, get involved with the projects that I list in the project sidebars in each chapter. These can lead to a deeper understanding of the concepts. Furthermore, these projects could encourage you to become a true electronic hobbyist—or is that a geek or nerd?

When you finish this book you will not be an electronic engineer nor will you be able to design or analyze circuits. But you will know about all the different kinds of circuits, how they work, and how they all fit together to create electronic equipment. The benefits to you are the ability to apply, use, select, operate, and to some extent troubleshoot most of the common electronics products with confidence, while appreciating their complexity and the value they deliver. Hope you like it.

Lou Frenzel
Austin, TX

Chapter 1

Learning About Electronics for Your Own Good

A Little Bit of Perspective Before You Get to the Details

In this Chapter:

- Why it is helpful to know electronics.
- The 10,000-foot view of the electronics industry and how it works.
- The systems view of electronics.

INTRODUCTION

You do not know how lucky you are. You live in high-tech heaven surrounded by lots of useful, entertaining, interesting, necessary, and even addicting electronic products, products you cling to and would not want to give up.

But do you have any idea how many electronic products you own? Do you really know how much electronics influences your life every day? Some of you do, but most of you probably do not because your electronic gadgets are pretty much taken for granted. Yet we spend the better part of our lives working with these devices. Most of us sit in front of a computer all day at work, slouch on the couch in front of the TV at night, listen to our iPods going to and from work, and spend a weekend downloading videos off of the Internet or taking photos with a digital camera. And let us be clear here, how many text messages did you send today or cell calls did you make? The impact on our lives of all this electronic equipment is almost overwhelming. In this chapter, I encourage you to think about how electronics impacts your life.

And that brings us to the subject of this book, learning how electronics works. If you want a first book in electronics that gives you the big picture about how electronic equipment works, this is it. I am not going to beat you to death with a lot of complex circuits and theory or math, only what you really need to know. Then I will go on to show you how each and every one of the products you use every day actually works.

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00001-1
Copyright © 2018 Elsevier Inc. All rights reserved.

IT IS NOT LIKE IT USED TO BE

It used to be that you learned electronics by playing around with resistors, capacitors, transistors, and other devices. You wired up simple circuits, built a one- or two-transistor radio, or even built a kit. But today electronics is so different that it is hard to do that anymore. Oh yes, you can still build little circuits and radios and other gadgets, but that is not how electronic products are made today. Electronic equipment today is made with integrated circuits or ICs that we also call chips. These chips are tightly packed on printed circuit boards with resistors and capacitors that you can barely see. It is more difficult than ever to experiment with these devices, much less troubleshoot and repair them. We are in that age of electronics where unless it is a big pricey piece of equipment, you throw a defective electronic product away and simply buy a newer and better one at a lower price.

Despite the complexity of today's electronic products, there is something just fascinating about them. Many of you actually want to know how they work. And despite their complexity, these products are actually understandable. It is possible to learn how these devices work without a whole lot of trouble. And you do not have to learn all the math and physics required by engineers to do so. This book takes the basic ideas of electronics and reduces them down to the lowest common denominator and shows you how to use those fundamentals and apply them to all of the fabulous electronic gadgets you have today.

WHAT IS IN IT FOR YOU?

There are some big benefits to being electronic literate. Take a look at some of them.

Satisfy your curiosity—Surrounded by so much electronics, you often probably wondered just how all this stuff works. For some of us, not knowing how something works nags at us until we satisfy that curiosity. If you have an interest in electronics, you tend to know more about it. This book will get you started in the right direction.

Enhance your hobby—If you dabble in a hobby that uses electronics, you obviously want and need to know more about it. Lots of hobbies involve electronics such as radio-controlled models, electric trains, amateur radio, shortwave listening, citizens or family radio, audio systems, or video. Or maybe you just like playing around with your home security system, garage door opener, or your high-speed Internet connection. A major part of any hobby is learning more about it and that is very satisfying. And do not forget, electronics itself can be your hobby. You can spend your time learning more about it and then digging deeper into those things that you want to know more about. Amateur radio is certainly one of those electronic hobbies that will take you from one extreme to the next in the radio spectrum. Anything having to do with computers is also a great hobby. With everything being controlled by an embedded microcomputer, spending more time learning about them is a great activity with nearly endless possibilities.

You are a maker—A maker is a serious do-it-yourselfer (DIY) who likes to build things small and large. Makers are hobbyists who like to create projects for home use or just for fun. Projects can be all electronic but more often involve wood or metal working and other skills. Most projects use electrical or electronic parts. That is why learning electronics is so important.

Job-related needs—You may actually be working in a job surrounded by electronic equipment of some sort, yet you do not know how it works. Often, just understanding some of the fundamentals will give you a better grasp of how to use that equipment or even troubleshoot and repair it. Understanding some of the concepts may actually help you to better select and purchase equipment that you may use.

Boost your school performance—For those of you going to a college or university to learn electronic engineering or technology, you regularly have your curiosity stimulated by the classes you take. Yet most of the classes are heavily involved with theory, physics, math, and circuit analysis. What you really do not get in school is the perspective or big picture as to how the electronic products actually work. This book will give you the big picture and show you how it all comes together so that all those detailed classes in circuits and theory will make more sense.

Just so you will not appear to be so dumb—With electronics everywhere, people often talk about it without really knowing what they are talking about. The ignorance of people who use the electronics but do not have a clue as to what it does or how it does is amazing. For instance, do you really understand what an MP3 is, or why 4K UHD TVs are better, or what a 4G or 5G cell phone really is? The answers are in this book. If you want to appear a little smarter to your coworkers, friends, and relatives, this book can help out. You will be able to deal with common questions and misconceptions, such as can you get shocked by a car battery, can you really get brain cancer or pop popcorn with your cell phone, or will sitting too close to your TV set make you sterile? While this book certainly will not make you a genius, it will indeed give you the basics so that you will not appear to be an idiot when technical questions about electronics come up.

ELECTRONICS: THE BIG PICTURE

Before we get into the nitty-gritty of how electronic equipment works, you really need to know the entire scope of electronics. It is a huge industry, and recent figures seem to show that it is one of the biggest, if not the biggest, markets in the entire world. To get a grasp of how big the industry is, we normally break it down into segments of specializations. There are five major fields of electronics: communications, computers, control, instrumentation and measurement, and components. Any electronic product or device will easily fall into one of those categories. In some cases, the product may overlap two or more or all of those categories. Take a look at Fig. 1.1, which shows each of these segments of electronics and the products and technologies that are part of them.

Communications	*Computer*	*Control*	*Instrumentation*	*Components*
Radio	Supercomputers	Automation	Test equipment	Resistors
Television	Mainframes	Robots	Test systems	Capacitors
Telephone	Servers	Manufacturing	Data acquisition	Inductors
Cable TV	Workstations	Automotive	Medical	Transformers
Satellites	Personal computers	Home control	Auto diagnosis	Diodes
Networks	Peripheral equipment	Appliances	Aircraft diagnosis	Transistors
Wireless systems	Embedded	Security		Integrated circuits
Consumer	Special purpose	Toys		Printed circuits
Cell phones				Wire and cable
				Connectors

FIGURE 1.1 Major sectors of the electronics industry and common applications.

Communications

Communications is the oldest segment of electronics and still the largest. Electronics actually started with communications—specifically telegraph, telephone, and radio—and grew from there. A lot of this book is about communications because it is such a huge segment of the industry and one that we use the most. And do not forget, communications comes in both wired and wireless forms. Wired systems include the vast telephone network, cable TV systems, and computer networks, including the Internet. Wireless systems comprise all of the radio, cell phone, television, satellite, radar, and other wireless systems.

Computers

Computers have only been around since the late 1940s and early 1950s but what an impact they have had on the way we work. Today virtually everyone uses and even owns a personal computer. And then there are all the larger and more powerful computers such as the servers that manage all of our networks, the mainframes still used by government and big business to manage huge databases, as well as the high-speed supercomputers that still do an amazing amount of scientific, engineering, and mathematical design and research. But the computer we are going to talk about most in this book is the embedded controller. These are small single-chip digital computers called *microcomputers* or *microcontrollers* or just *micros* that are literally part of every electronic product. These are miniature digital computers dedicated to a specific function inside the products in which they exist.

Control

Control is a broad general term for monitoring and control. Monitoring, of course, means sensing various physical characteristics such as temperature, humidity, physical position, motor shaft speed, or light level. Electronic devices called *sensors* or *transducers* convert these physical characteristics into electrical signals, which allow us to monitor them. Control refers to managing

and exercising some degree of influence over items such as motors, lights, relays, heating elements, and other devices. Most monitoring and control functions take place in factories, chemical plants, refineries, and food processing operations. Control also occurs in the home, an example being your electronic thermostat. It also shows up in electromechanical products such as a DVD player. Electronic controls appear in appliances, home control systems, security systems, automobiles, and even toys. Robots are another major segment of the control industry.

Instrumentation

Instrumentation refers to the field involved with testing and measuring electronic equipment and other mechanical or electronic items. It refers to the test instruments such as voltmeters, oscilloscopes, and spectrum analyzers as well as the large automated test systems used for mass testing and measuring of other devices. Instrumentation refers to data acquisition systems, medical tests and measurements, and a wide range of other products.

Components

All of the electronic products that make up each of the four major segments of the electronic industry are made up of various electronic components. In the past, electronic products were made of the individual discrete components such as resistors, capacitors, diodes, and transistors. Today most electronic equipment is made with one or more ICs surrounded by a sprinkling of those other so-called *discrete* components. No longer can we access most individual components or circuits since they are sealed within ICs or chips. Just keep in mind that there is a whole industry centered on making these electronic components that are in turn made available to the manufacturers of the end electronic equipment in each of the four major categories just described.

HOW THE ELECTRONICS INDUSTRY WORKS?

As part of the big picture of learning electronics, you really need to understand how the industry itself works. This is summed up by the simplified block diagram in Fig. 1.2. It all starts with the raw materials that the component manufacturers use to create the individual components. For example, sand is refined into silicon, which, in turn, is converted into wafers that are processed into the ICs we use.

The electronic equipment manufacturers design the electronic equipment for the marketplace. It may be a TV set, a cell phone, or a military radar. These companies buy the electronic components and put them together to create the end product. Manufacturers may then sell the end product directly to customers

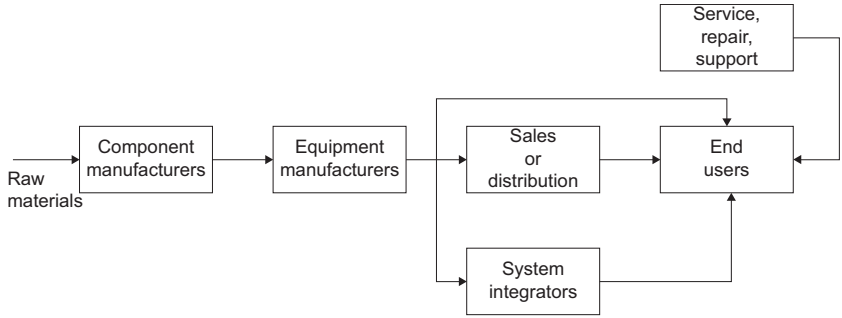


FIGURE 1.2 General block diagram of how the electronics industry works from raw materials to end users.

and end users. In some cases, the end product will go through a sales organization or distributor of some sort. Your LCD large-screen TV set does not come directly to you directly from Samsung in Korea or Sony in Japan. It is sold to an organization such as Best Buy or Amazon, which is where you buy it. Sometimes the electronic equipment is sold to so-called systems integrators. These are companies that piece together larger systems for an end user (like the military) made up of a wide range of different types of equipment.

Finally, there are the customers or end users of the equipment. These come from a wide range of backgrounds. The end users or customers may be businesses with offices, industry with factories and process control plants, or the government, military, hospitals and other medical organizations, schools, colleges and universities, and you the consumer. There is also a network of service companies designed to support customers. They may do installation or repair work that the customer is not capable of doing.

Electricity Versus Electronics

One of the questions that always comes up in the early stages of learning about electronics is: what is the difference between electricity and electronics? Let us get this straight up front. Electricity refers to the basic energy we use for power. It generally involves the generation and distribution of electrical energy to homes, businesses, and factories. Electricity is energy that is produced by the coal-fired or nuclear power plant and then sent to you over long transmission lines until it comes into your house where you access it through your AC wall outlets. You use that energy for lighting and appliances and also to power most of your electronic equipment.

Electrical power may also be generated for use in other systems. The electrical system in a car is a great example. It uses a battery plus a generator driven by the automobile engine to recharge the battery and to operate all of the electrical and electronic devices in a car. Ships, airplanes, and offshore drilling rigs also

have their own electrical power–generating systems. The new electric wind generators and solar power systems are also electricity-producing systems.

All of the principles of electricity also apply to electronics. Basic electrical components such as resistors, capacitors, inductors, transformers, motors, and other similar devices are also used in electronics.

Electronics is the field of science that uses electrical principles to perform other useful functions. Electronics is the control of electricity to produce radio, television, computers, robots, and MRI machines. To control the electricity, you need more than just basic electrical components such as resistors and capacitors. What makes electronics possible are the unique components called *transistors*. Electronics began, of course, with vacuum tubes and then switched over to transistors as the main control devices. Transistors are now miniaturized and packaged in devices called *integrated circuits* that perform very specific electronic functions, such as generating signals, amplifying signals, or performing some control function. Just keep in mind that it is the control devices such as transistors and the circuits that they comprise that make electronics what it is. The transistors are used to form circuits that in turn perform all of the various functions required to produce electronic devices.

THE PAINFUL TRUTH

Okay, here comes the hard part. Electricity is moving electrons. An electron is a tiny particle that is inside the atoms that make up everything we can feel, see, and even not see. If we can get some electrons moving together in a wire, electrical or electronic component, or circuit, we can control them to do many useful things, such as amplification, for example. Moving electrons make up what we call *current flow*. And current flow is produced by electrical energy called *voltage*. Voltage comes from batteries, the AC wall outlet, and lots of other sources including power supplies, solar cells, microphones, and the like. If we can control the electrons, we can produce magic results. That is what electronics is all about.

We control the electrons with components such as resistors, capacitors, inductors, transistors, and all sorts of ICs. We create circuits that actually process the electron flow. We can call the voltages that create current flow and the resulting current *signals*. The circuit processes the signals to produce the end effect that we want, be it a radio, a computer, or a DVD player.

One of the basic models I will use in this book is shown in Fig. 1.3. Think of electronic signals as the inputs to a circuit or piece of equipment that processes the signals producing new signals that represent the output we want. Think of the small voltage that comes from a microphone when you talk into it. It is basically too small to be useful. So we apply it to a circuit called an *amplifier* that makes the signal bigger and more useful. That amplifier processes the signal to make it large enough to drive a speaker as our desired output. The result is a

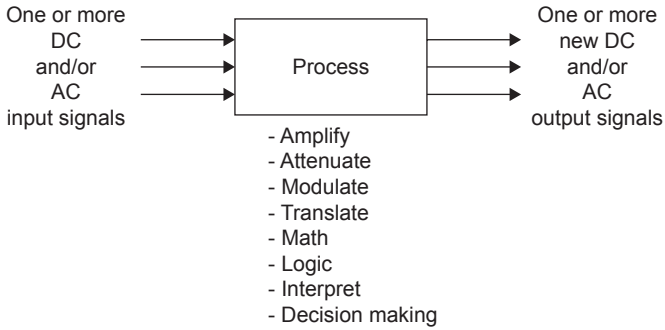


FIGURE 1.3 Model of how all electronic circuits and equipment work. Input signals are processed by circuits and equipment into new output signals.

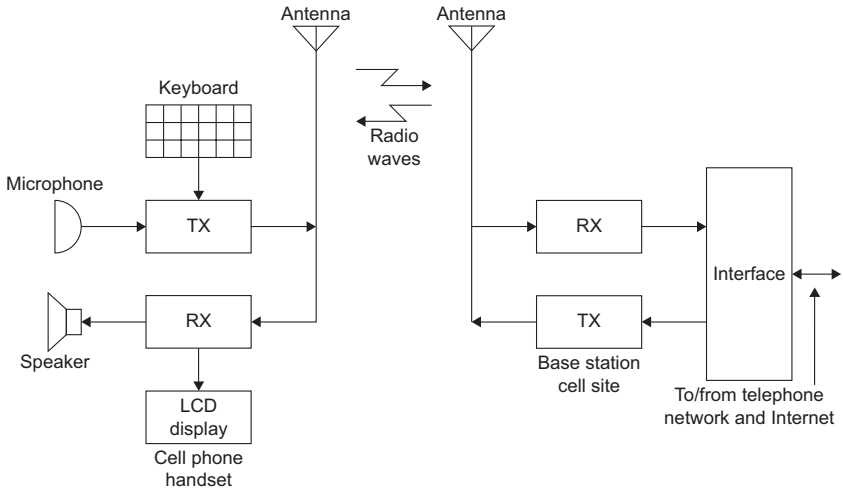


FIGURE 1.4 Model showing how a cell phone communicates with a cell site to make a call.

public address system. Anyway, you get the picture. Just remember that *all* electronic circuits and equipment are based on this model: input–process–output. Think about it.

Here are a couple of other examples to show how most electronic things work.

Cell Phone

Take a look at Fig. 1.4. On the left is a cell phone handset. It is made up of two major pieces—a transmitter (TX) and a receiver (RX). You talk into a microphone and generate a small electrical voltage or signal representing your voice.

The transmitter takes that and processes it in such a way that the voice controls or modulates a high-frequency radio signal. That signal carrying your voice is then radiated by the antenna to a cell site or base station. The base station receiver picks it up and processes it back into the original voice signal where it then undergoes other processing before being sent over the telephone network to its destination. The dialing process or text messaging from the keyboard also generates input signals that are transmitted to the base station.

On the return side, the voice from your caller passes through the cell phone network to the base station and it is then used to control the transmitter to send that voice to you by radio. The transmitter sends the signal to the antenna that sends the signal to the receiver in your cell phone. The receiver processes the signal by amplifying, demodulating, and otherwise processing the voice that eventually is sent to the speaker that is glued to your ear. Another output may be a text message on the liquid crystal display (LCD).

Computers

The main function of a computer is to store and retrieve data, process data, and to provide automatic control. Data consists of information, facts, and figures. It may be numbers, letters, symbols, or text of any kind. It might represent names and addresses, parts inventory, accounting or banking figures, control signals, or a variety of other items. Data may also be graphics and illustrations, or voice and video that are converted to data. Such data can be stored electronically in computers and rapidly accessed.

Computers process or manipulate data in many different ways. They can perform mathematical operations on it, sort it, edit it, translate it, or otherwise operate on it to produce some useful output. Computers also make decisions based on the data.

Computers have so many applications that it is difficult to enumerate them. In general, computers are tools that help people organize and perform their work in a more efficient manner. Computers also allow people to do work that was difficult or impossible to do without computers. Computers perform accounting and banking operations; store and process mailing lists and employee records; solve complex mathematical problems in business, science, and engineering; and create graphics. The thing that makes them so valuable is that all of their operations are automatic. Humans need not be a part of the actual computation, as is necessary with a calculator. Computers carry out preprogrammed assignments to solve various problems or perform operations. Most operations are extremely fast. It is this automatic feature that makes computers so useful.

All computers, regardless of their size and features, are made up of the four basic sections shown in Fig. 1.5. The memory electronically stores the data to be processed, as well as the program that tells how the data is to be manipulated.

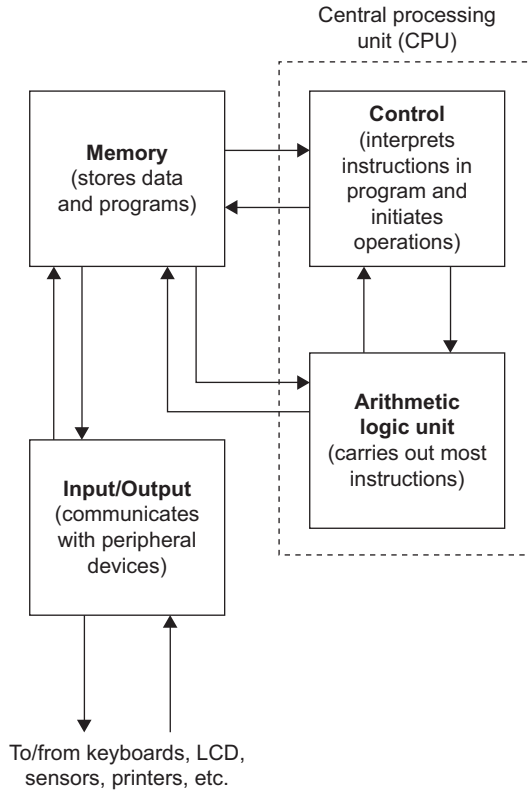

Central processing unit (CPU)
Memory (stores data and programs)
Control (interprets instructions in program and initiates operations)
Arithmetic logic unit (carries out most instructions)
Input/Output (communicates with peripheral devices)
To/from keyboards, LCD, sensors, printers, etc.

FIGURE 1.5 Block diagram representing any digital computer, be it a mainframe, PC, or embedded controller.

The program is a sequence of codes or instructions that cause the computer to carry out its preprogrammed assignment one step at a time.

Refer again to Fig. 1.5. The control section examines the program instructions one at a time in sequence, interprets them, and then sends control signals to all other parts of the computer. The desired operations, such as store, add, print, and so on, are carried out.

The arithmetic logic unit (ALU) is the section that actually carries out most of the processing. It performs data transfers, arithmetic operations, and logical decision-making. In most computers, the control and ALU sections are integral units that work closely together. They are usually referred to as the central processing unit (CPU). A microprocessor in a personal computer is a single chip or a CPU.

The input/output (I/O) section in Fig. 1.5 is the interface between the computer and the outside world. It communicates with peripheral devices that humans use to input programs and data, and receive the output results of

computation. Data and instructions are usually entered via a keyboard, while outputs are displayed on a video screen or printed out. Inputs may come from sensors, and output may go to a printer or LCD readout.

There are many sizes and types of computers. Supercomputers are the largest and fastest computers. They are used primarily for difficult, complex scientific and math problems. Mainframe computers are also very large, and they are used by business and government for financial applications, data storage, and other applications. Personal computers are the smallest practical computers in use. Millions of them are used for word processing, financial spreadsheets, database management, and email and Internet access.

There are also many dedicated computers, built into other equipment to perform single-purpose operations unlike the general-purpose data processors described above. Thanks to semiconductor technology, it is now possible to put an entire computer on a single chip you can hold in your hand. These are called *embedded computers* or *microcontrollers*. These microcomputers are used like components and are built into most other kinds of equipment such as TV sets, microwave ovens, gasoline pumps, washing machines, and many others. Virtually every other electronic product contains at least one or more embedded controllers. And even very large ICs have controllers on the same chip called *cores*.

Robots

A great example of a control device is a robot. Most robots consist of an electromechanical manipulator arm used in manufacturing operations. Robots are machines designed to mimic human capabilities. Most robots simulate a human arm and hand. As a result, a robot may be able to substitute for a human in certain manufacturing jobs. A typical robot manipulator arm is shown in Fig. 1.6. Motors operate shoulder, elbow, and wrist joints, while grippers and other tools form the hand that does the work.

Robots help automate the manufacturing process to increase productivity. They lower costs, produce more goods in less time, and improve quality. Robots also replace humans in many jobs requiring repetitive, tedious, and hazardous work.

Robots perform a variety of tasks in industry. The most common are welding, spraying or painting, and "pick-and-place" operations. Various tools on the end of the manipulator arm, called *end effectors*, let the robot perform a remarkable variety of tasks. In addition, a programmable controller or computer is used to control the robot. A robot may thus be programmed to perform a wide variety of jobs and is easily reconfigured when the work changes.

In subsequent chapters you will see more of these kinds of descriptions. But in Chapters 2–4, you will learn a few more basics that make the rest of the book more understandable.

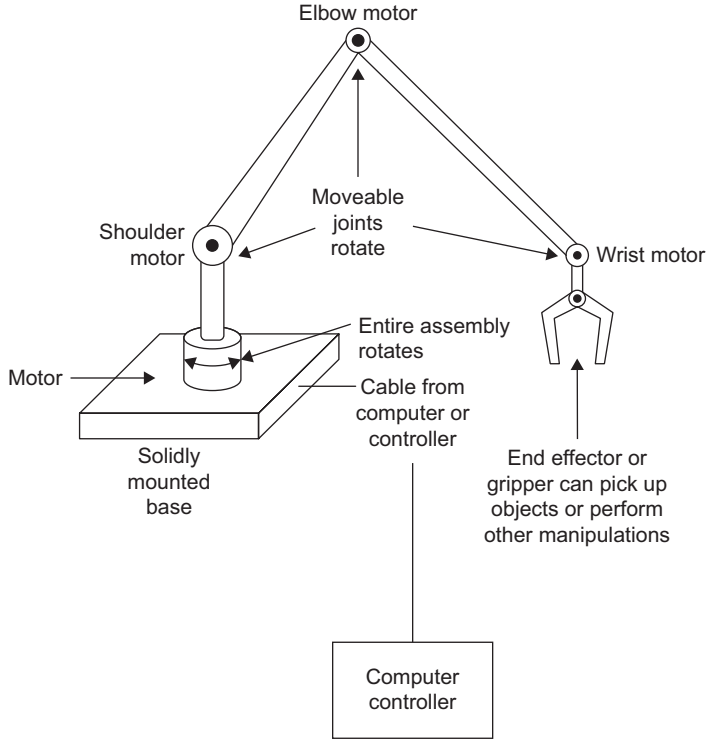


FIGURE 1.6 The most common form of robot emulates a human arm and hand to perform work automatically under the control of a computer.

Project 1.1

How Much Electronics Do You Own?

Just to be sure that you really appreciate the extent to which electronics impacts your life, I strongly suggest that you take a few minutes and make an inventory of all the electronic devices and equipment that you use at home, at work, and away from home. Get a yellow pad and a ballpoint pen and move around your house and just write down all the electronic products that you own and use on a regular basis. TV sets, computers, and cell phones are the most obvious, but do not forget things such as telephones, your wrist watch, appliances, and other entertainment products. Make a separate listing of the electrical and electronic products you use inside your car and then another one for those electronic products that you use at work. Make the list comprehensive. Study it. Be amazed.

Project 1.2

How Much Electronics Do You Use?

Now take that same pad of paper and pen and make a quick summary of how you spend your time during the day. How much time do you spend using each of the electronic products that you listed above? Some of them are only momentarily used, but others you use over longer periods of time, particularly computers, smartphones, and TV sets. Just take a quick estimate of the time you use each one during a typical day. Again, add up the hours. Be amazed.

Project 1.3

Decisions, Decisions

Make the following decision. If you had to give up all of your electronic products but one, which one would you keep? TV, cell phone, remote control, music player? Only one. This will say a lot about who you are.

This page intentionally left blank

Chapter 2

Electronic Concepts: More Interesting Than You Think

Some Basic Stuff You Really Need to Know

In this Chapter:

- Electrons and current flow.
- DC and AC voltage.
- Voltage sources, batteries, the power line, and power supplies.
- Signal sources.
- Magnetism and induction.

INTRODUCTION

You do not have to be an engineer, physicist, or mathematical genius to learn electronics. But there are a few basic things that you need to know so you can understand what is going on in the circuits and equipment. For example, you need to know that electrons are what make up current flow, and voltage is what makes the current flow. You also need to know about magnetic fields and electric fields, where they come from, what they do, and how magnetism and current flow are related. With that background you are ready to learn about the various components and circuits. This chapter takes care of those basics.

ELECTRICITY AND ELECTRONICS

Electricity is a type of energy produced by a charge that is either fixed (static) or moving (dynamic). The main source of electricity is the electron, a subatomic particle that has a negative charge. When electrons are stored or moved, electricity is produced.

Electricity is one of our prime sources of energy. It is used for lighting, heating, and operating appliances of all sorts. It powers motors to produce mechanical energy, and it powers our electronic equipment. The uses of electricity are virtually infinite.

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00002-3
Copyright © 2018 Elsevier Inc. All rights reserved.

Electronics is the field of applied science that uses components such as resistors, capacitors, diodes, transistors, and integrated circuits (ICs) to control and process electricity. These components are used to create circuits that convert, modify, vary, translate, or otherwise manipulate electrical charges to perform useful functions. That is the essence of it. Now for the details.

Atoms and Electrons

This section really ought to be called Physics 101, but I do not want to scare you away. Just to make you more comfortable, I have to say that it is not all that complicated or difficult to understand. So even if you avoided physics in high school, just be aware that it is pretty easy. Trust me.

All matter, whether it is a solid, a liquid, or a gas, is made up of tiny entities called atoms. An atom is the smallest possible particle of substances called elements. An element is a chemical substance that cannot be subdivided into smaller, simpler substances. Typical elements are hydrogen, oxygen, gold, silver, copper, carbon, helium, silicon, and sodium. All matter is either an element or composed of several elements. Atoms of two or more elements often combine to form new substances called compounds. For example, water is a compound of hydrogen (H) and oxygen (O) or H_2O. Salt is a compound of sodium (Na) and chlorine (Cl) or NaCl. The smallest possible particle of a compound that exhibits all the characteristics of the substance is called a molecule.

According to the theories of physics, an atom is composed of a nucleus consisting of a core of tightly bound subatomic particles, called protons and neutrons. Protons have a positive charge. Neutrons are neutral, having neither a positive nor a negative charge.

Rotating around the nucleus are electrons. The electrons arrange themselves in multiple orbits in much the same way that the planets orbit around the Sun. The orbits are sometimes referred to as rings or shells. Electrons have a negative charge. Fig. 2.1 illustrates a copper atom. The number of electrons in orbit equals the number of protons in the nucleus. The number of positive charges equals the number of negative charges. Therefore, the atom is balanced electrically.

As far as electronics is concerned, the most important part of an atom is its electrons. Since electrons can be manipulated (i.e., stored or moved), they can be used to produce electricity. This electricity can then, in turn, be processed and controlled to perform a wide range of valuable functions. By applying an external force, the electrons in the outer shells can be stripped off to produce current flow.

Charge, Voltage, and Current

There are two basic types of electricity, static and dynamic. Static electricity is the buildup of a charge between two objects. Dynamic electricity supplies a continuous charge.

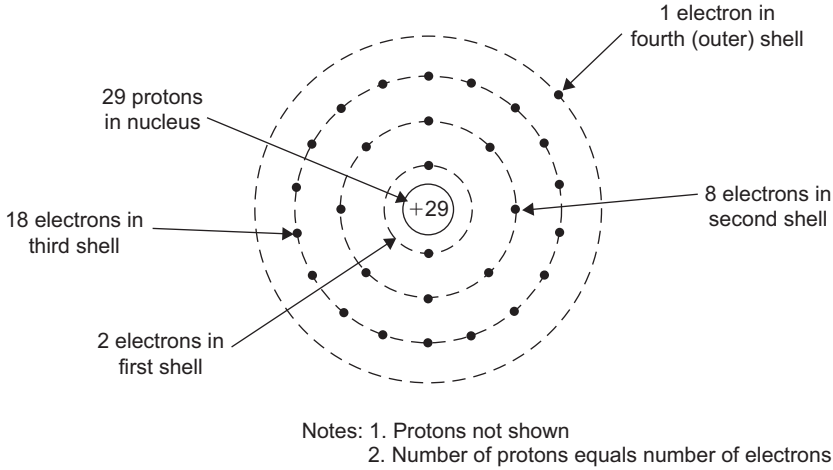


FIGURE 2.1 Physics model of what a copper atom looks like.

Static Electricity

With static electricity, one object has an excess of electrons and the other has a shortage of electrons. The object with an excess of electrons is therefore negative, while the object with a shortage of electrons is positive. A basic law of electricity states that opposite charges attract and like charges repel. The two oppositely charged bodies, one negative and one positive, will have a high physical attraction for one another. An invisible force field called an *electric field* will exist between the two charged objects. The object with a shortage of electrons attracts the object with excess electrons.

The two oppositely charged objects will naturally attract one another. The closer they are, the greater the attraction. This attraction of the charges sets up an electrical force field between the two bodies. This electric field, like a magnetic field, contains energy that can be released to perform useful work.

Whenever there are opposite charges on two objects, we say that an electrical potential or difference of potential exists between them. This difference of potential is called *voltage*. Voltage is an electrical pressure that can cause work to be accomplished.

The charge stored on the two objects is usually called static electricity because it is stationary. However, this charge is usually dissipated in some way. If the two charged objects get too close, or the charge builds up too high, the attractive force becomes so great that the electrons jump the gap between them and create a spark. That is how lightning occurs. The clouds and the earth become oppositely charged, the earth positive, the clouds negative. The charge becomes so great that the electrons leap across the free space gap, ionizing the air, and creating a path through which the electrons travel to neutralize the

positive charge on the earth. The result is the massive spark or flash that we call lightning and the roar we call thunder.

In general, static electricity is not very useful. It represents energy stored as a charge, but it quickly dissipates as a spark or a brief flow of electrons between the negatively and positively charged objects when the two charged objects get close enough or when the charge gets too high. We call this an *electrostatic discharge* (ESD). Static electricity, or ESD, is regarded as more of a disadvantage or nuisance than anything else. In fact, it is one of the main causes of damage to electronic components such as transistors and ICs.

Neutralizing a charge between two objects cancels or eliminates the potential. However, if we had a constant charge that could constantly be replenished, we would have a continual source of potential (voltage) and could therefore sustain a flow of electrons. With such a source of electrical energy, useful work can be accomplished.

Dynamic Electricity and Current Flow

Electricity as we know it, whether in electrical power applications or in electronics, is actually the flow of electrons. Electrons flowing from one place to another is known as current flow. And it is voltage that causes the current to flow. When electrons flow, we have energy that can be put to practical use. Electrons flowing in a filament create light. Electrons flowing in a heating coil produce heat. Electrons flowing in a motor produce mechanical energy. The object is to convert the energy from one form to another. In electronics, we precisely control the electrons with special components and circuits to produce a variety of effects.

Fig. 2.2 provides a general block diagram model that shows how all electrical or electronic circuits work. A voltage source produces the energy that causes electrons to flow. This current flow is controlled or processed by a single electronic component, or many components that make up an electronic circuit. The processed electrons flow through a load that consumes or uses the electrical energy to produce a useful output. In an electrical application, the load may be a light, a heating element, or motor, as described above. In an electronic application, the load may be an antenna that radiates the radio signal produced by the electronic circuits. Or the load may be the magnetic head that develops and records digital data on a hard disk or a laser that records a video signal on a DVD.

A couple of key facts about the circuit in Fig. 2.2 are required here. First, there must be a voltage source to cause the current to flow. The electrons flow from the negative terminal of the voltage source around the circuit as they are attracted by the positive terminal. Second, the circuit must always form a complete loop from plus to minus.

Current is so important that we need some way to measure it. We do this by standardizing the number of electrons that move past one point in a

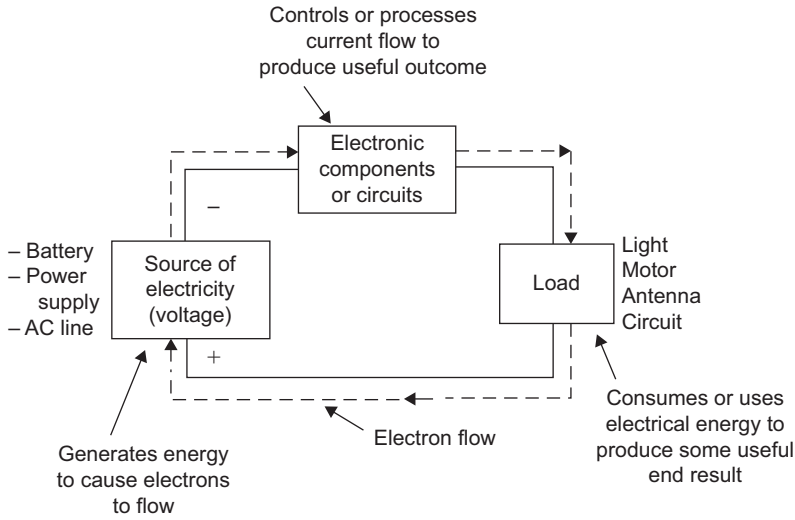


FIGURE 2.2 Basic electrical circuit used to describe every electronic circuit.

conductor during a specific period of time. The charge or quantity of electrons (Q) is measured in coulombs (C). One coulomb of charge is equal to 6,242,000,000,000,000,000 or 6.242×10^{18} electrons. If 1 coulomb moves past a point in 1 s, we say that the current is 1 ampere (A). One coulomb per second (1 C/s) equals 1 A.

Direction of Current Flow

The current flowing in electronic components and circuits consists of electrons that are influenced by a charge or voltage source. The early pioneers of electricity did not know that electricity was the movement of electrons. They knew that there was some kind of movement, of a charge or current, but they did not know what it was, or in which direction it flowed. To explain electrical phenomena and perform analyses of components and circuits, they simply assumed a direction of current flow that everyone agreed to and used. Their original assumption was that current flowed from positive to negative, the opposite of the actual direction. This has become known as conventional current flow.

Even after the discovery that real current was electrons moving from negative to positive, scientists and engineers continued to assume a positive-to-negative current flow. And science and engineering professors have continued to teach and support the conventional current flow concept. Most science and engineering textbooks illustrate and teach conventional current flow. Old traditions die hard or maybe never die.

As it turns out, it does not really matter what direction current flows. Any analysis, design, or explanation can be successfully carried out using either

electron flow or conventional current. One way is not any better than the other in describing or understanding electrical or electronic phenomena. Why academia has perpetuated the myth of conventional current flow rather than accepting and teaching the truth is not known. It no doubt stems from long-time heritage, custom, and convention.

Conductors, Insulators, and Semiconductors

A conductor is a material that has many electrons easily freed up by an external voltage. Current flows through conductors easily. They have what we call low resistance. Most good conductors are metals such as copper, silver, or aluminum, with loosely bound electrons that can be freed by an external voltage to create current flow. Copper wire is the most commonly used conductor because of its low cost and its ability to be formed into many different shapes and sizes. Most metals are conductors but so is salt water.

Insulators are just the opposite of conductors. These are usually compounds in which the electrons are tightly bound together with the nuclei of the atoms. Even with lots of voltage applied, the electrons are hard to strip away to make current. Insulators keep current from flowing. Some common insulator materials are glass, ceramic, and plastics.

A third category of material is called *semiconductor*. It is a material that can be changed to make it a good conductor or a good insulator or anything in between. Semiconductors are used to make the transistors, diodes, and ICs. The most common semiconductor is silicon. Others are germanium and carbon. Compounds such as gallium arsenide (GaAs), indium phosphide (InP), and silicon germanium (SiGe) are examples. Most ICs or chips are made of silicon.

MAGNETISM

You are probably asking, what does magnetism have to do with anything? As it turns out, it has lots to do with electricity and electronics. As you will see, the two are tied together significantly, meaning you need to know about both to get the big picture. Magnetism is essential to all electrical and electronic phenomena. Without magnetism, there would be no electricity or electronics.

Magnetic Fields

Magnetism is an invisible force that has the power to attract pieces of iron, or alloys of iron such as steel. Iron, steel, and the metals, nickel and cobalt, are called magnetic materials because they can be magnetized to generate a magnetic field, or they support the development and passage of a magnetic field. Magnets are pieces of such materials that exhibit this force. Magnetism has no effect on nonmagnetic materials such as other metals (aluminum, brass, etc.) or on objects made of wood, plastic, or glass.

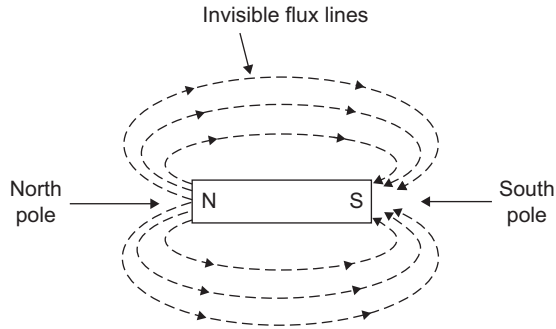


FIGURE 2.3 Permanent bar magnet illustrating the magnetic lines of flux that surround it.

You have no doubt experienced the effects of magnetism yourself. You may have played with a horseshoe magnet as a kid or used bar magnets like the one in Fig. 2.3 in a school lab. And you most likely have used flat magnets to hold paper notes on your refrigerator or file cabinet. These are called permanent magnets because they retain their magnetic force indefinitely.

A magnet is surrounded by an invisible magnetic force field made up of magnetic lines of force or flux lines. These flux lines flow out of one end of the magnet, the north (N) pole, and into the other end, the south (S) pole, as shown in Fig. 2.3. The ends of the magnet are the points of the heaviest concentration of the magnetic field.

The basic law of magnetism follows: *opposite poles attract, and like poles repel.* When you get two permanent magnets together, the north and south poles will attract one another. On the other hand, two north poles will repel one another. Two south poles will also physically push away from one another. Permanent magnets are used in a variety of electrical and electronic equipment. Their most common use is in motors, where the attraction and repulsion of magnets create rotary motion.

Electromagnetism

Magnetism is also produced by electricity. Whenever electrons flow in a conductor, they produce a magnetic field. This effect is called *electromagnetism*. Fig. 2.4A shows how the magnetic lines of force encircle a wire through which current is flowing. Note that the direction of the lines of force depends on the direction of the current flow.

The strength of the magnetic field around a wire depends on the magnitude of the current flowing. High current (composed of many electrons) produces a strong magnetic field. Despite the current amplitude, however, the magnetic field weakens because it spreads out quickly, even at a short distance from the wire.

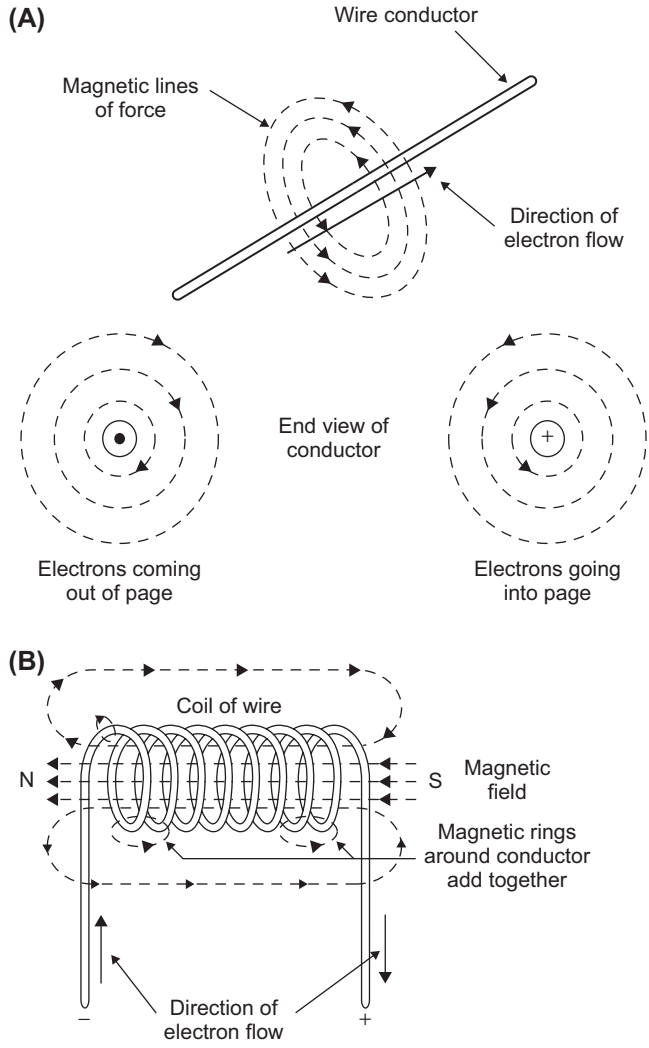


FIGURE 2.4 (A) Current in a wire produces a magnetic field around it. (B) Coiling the wire increases the strength of the magnetic field.

If you make a coil out of the wire, as shown in Fig. 2.4B, the lines of force around each turn are added together. The result is that a more powerful, highly concentrated magnetic field is produced. In fact, the coil simulates a bar magnet with north and south poles.

As indicated earlier, the strength of the magnetic field depends on the current amplitude in the wire. High current produces a strong field. The magnetic field is also increased by coiling the wire, which helps concentrate the lines of force. The closer the turns of the wire, the stronger the field. You can also increase

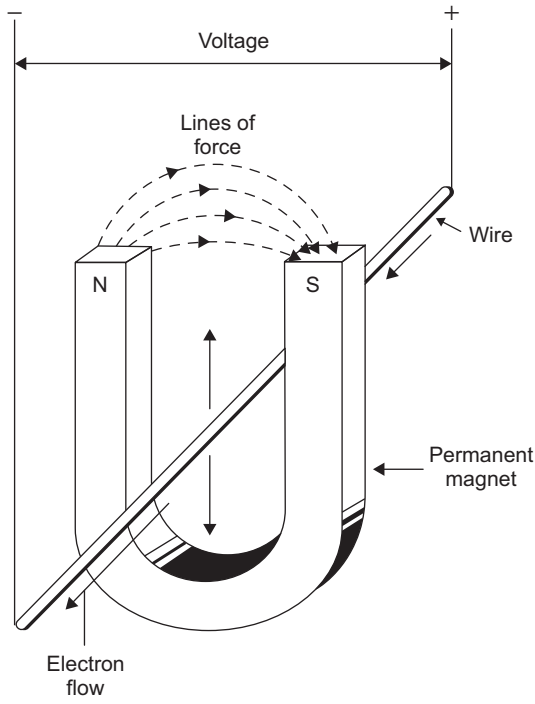


FIGURE 2.5 Relative motion between a magnetic field and a conductor such as a wire causes a voltage to be induced into the wire making it a voltage source.

field strength for a given current level by simply adding more turns to the coil. Strong electromagnets are made by tightly coiling together many turns of fine wire in several layers.

Another way to increase the strength of the magnetic field is to insert a bar or core of magnetic material inside the coil. Because flux lines flow easier in iron or steel than in air, an iron or steel bar inside the coil helps concentrate the lines of force. Most of the flux lines flow through the core because it represents a lower path of resistance than the surrounding air for the lines of force. The result is a very strong field.

Electromagnetic Induction

Another important principle of magnetism is electromagnetic induction. This principle states that whenever there is relative motion between a conductor and a magnetic field, a voltage will be induced into the conductor.

Refer to Fig. 2.5. If the wire is moved up or down so that it cuts through the magnetic lines of force between the magnet poles, voltage will be induced in the wire and cause current to flow. Voltage will also be induced into the wire

if the wire is held in a fixed location and the magnetic field is moved so that the flux lines cut across the wire. The wire actually becomes a voltage source. That voltage will cause current to flow. The direction of current flow in the wire depends on both the direction of the magnetic field and the direction of the relative motion between the magnetic field and the wire.

The amount of the induced voltage depends on the number of flux lines cut and the speed of cutting. The greater the number of lines of force, the higher the induced voltage and the greater the current flow. The highest induced voltage occurs when the conductor cuts across the flux lines at a right angle. If the wire moves parallel with the lines of force, no voltage is induced.

The induced voltage can also be increased by coiling the wire. More turns passing through the magnetic field will produce greater induced voltage and current flow. The motion in the magnetic field causes a small voltage to be induced into each turn of wire. All of the voltages will add together to produce a higher voltage.

In the examples above, we have assumed that the magnetic field comes from a permanent magnet. However, it does not really matter where the field comes from. An electromagnetic field works just as well. Electromagnetic induction is the principal method of generating electricity in the world. Most electrical power is produced by giant generators containing large coils of wire that rotate in a magnetic field. The generator or alternator in your car works the same way.

VOLTAGE SOURCES

To make current flow, we must have voltage. That voltage will produce either direct current (DC) or alternating current (AC). DC is electron flow in only one direction. AC is current that flows in one direction and then reverses and flows in the opposite direction.

Direct Current Voltages

DC may be a fixed, steady current, one that varies, or one that switches off and on periodically. A DC voltage source is one that causes direct current to flow one way through the circuit, component, or conductor. It has positively and negatively charged terminals of a fixed polarity. It always causes electrons to flow from negative to positive.

Fig. 2.6A shows a fixed, positive DC voltage source, which is usually either a battery or an electronic power supply. We call it a positive source because the negative terminal of the DC source is connected to a common point called the *ground*. The other terminal is positive with respect to ground. Voltages are always looked at or measured between two points with one point (ground) being the reference. The polarity of the voltage is the polarity of the terminal not connected to ground.

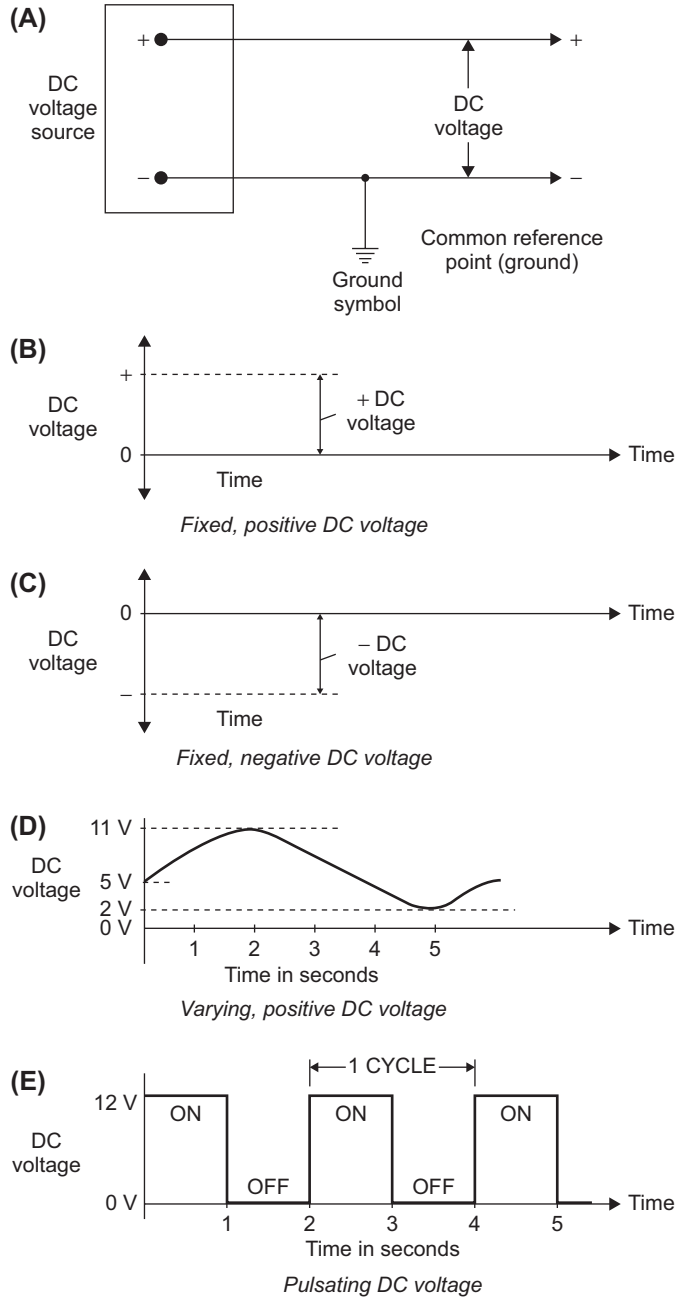


FIGURE 2.6 DC voltages. (A) DC voltage source such as a battery or power supply. One side is usually grounded to serve as a reference. (B) Fixed, continuous positive DC voltage shown over time. (C) Negative DC voltage. (D) Varying positive DC voltage. (E) DC voltage pulses.

The remainder of Fig. 2.6 shows graphs of DC voltage over time. In electronics we normally view DC or AC voltages with respect to time. The positive DC voltage is shown in Fig. 2.6B as a horizontal dashed line.

A negative DC voltage is shown in Fig. 2.6C. The dashed line representing the voltage below the zero line indicates that it is negative. The voltage is negative with respect to the reference point known as ground.

Fig. 2.6D shows a varying positive DC voltage. It begins at +5 V, rises upward to +11 V, and then drops to 12 V over a period of 5 s. The left-hand scale indicates the voltage level.

Fig. 2.6E shows a pulsating DC, that is, one that turns off and on. This voltage switches on to +12 V, stays on for 1 s, and then switches to zero for 1 s. Then this on–off cycle repeats. One cycle is the time of one on pulse and one off pulse or in this case 2 s. Such pulse signals are usually called *binary* or *digital signals*.

Alternating Current Voltages

As its name implies, AC current flows in two directions in a conductor, component, or circuit, but not at the same time. The electrons move in one direction, then reverse and flow in the other direction, both for a short period of time. The direction of flow reverses repeatedly.

The polarity of an AC voltage reverses periodically. During one period, the terminals of the voltage source are + and −, but later reverse to − and +. This reversal continues to repeat as the voltage amplitude varies. Since it is the voltage that causes current to flow, if the polarity of the voltage changes, then naturally the direction of the electron flow will also change periodically. The electrons just flow back and forth in the circuit.

An AC voltage source is usually represented by just a circle with a varying wave inside as illustrated in Fig. 2.7A. It may be the AC outlet in your home, a signal generator, or a type of electronic circuit called an *oscillator*. AC voltages and currents can assume many shapes. The most common electrical and electronic AC voltage is a sine wave, as shown in Fig. 2.7B. The voltage rises gradually from zero to a positive peak, and then drops to zero. Then it reverses polarity, rises to a negative peak, and returns to zero. Each rise and fall is called an alternation. One positive and one negative alternation form a cycle. The cycles repeat over and over. The number of cycles that occur per second is called the frequency.

The AC power-line voltage that comes into your house and appears at the outlets is a sine wave. Its frequency is 60 cycles per second (cps). The term *hertz* (abbreviated Hz) is normally used instead of cps to express frequency. The power-line frequency, therefore, is 60 Hz. All radio signals are sine waves, but have very high frequencies.

AC signals can have a variety of other shapes as well. Fig. 2.7C shows a square or rectangular wave. It is made up of pulses of alternating polarity voltages that switch from 16 to 26 V. Fig. 2.7D shows a triangular wave, and Fig. 2.7E

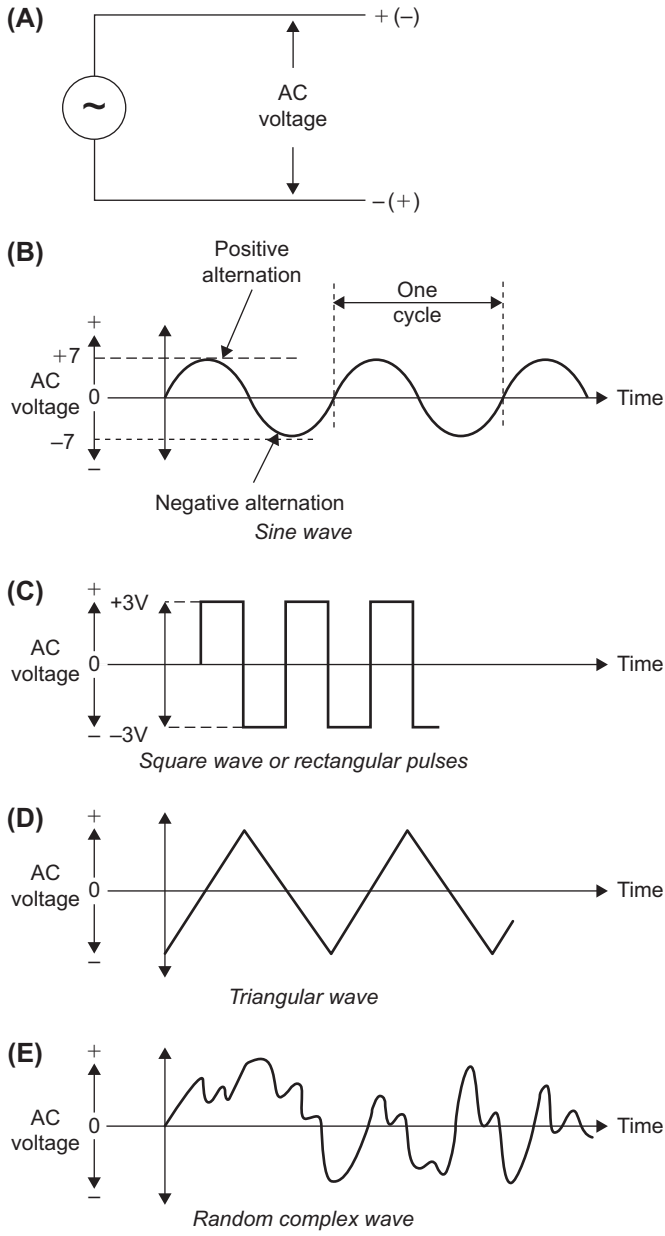


FIGURE 2.7 AC voltages. (A) AC voltage source drawn as a circle with a wave inside. The output polarity changes periodically. (B) Sine wave, the most common AC voltage shape. (C) Rectangular wave or AC pulses. (D) Triangular wave. (E) Random AC wave that may represent voice or video.

shows a complex waveform that might represent voice or video. Regardless of their shape, AC signals have one thing in common: they reverse the polarity and direction of current flow periodically. Their frequencies can range from a fraction of a cycle per second to billions of cycles per second.

Alternating Current Frequency

Frequency is measured and expressed in units called cps or Hz. Hertz is the more common unit. To express higher frequencies, the units kilohertz (kHz), megahertz (MHz), and gigahertz (GHz) are used.

1 kHz = 1000 Hz
1 MHz = 1 million Hz or 1000 kHz
1 GHz = 1 billion Hz, 1 million kHz, or 1000 MHz

Table 2.1 presents a summary of various frequency ranges that you will encounter and the types of signals in those ranges.

Alternating Current Voltage Measurement

To measure or represent the amount of AC in a circuit, we usually state the peak, peak-to-peak, and root mean square (rms) values. The peak value of a wave is simply the voltage measured from the zero line to the maximum positive (or

TABLE 2.1 The Frequency Ranges of the Electromagnetic Spectrum and Their Applications

Frequency Range	Types of Signals
20 Hz to 20 kHz	Audio, sound, voice, and music.
300 kHz to 3 MHz (LF)	Low radio frequencies. AM broadcast.
3 MHz to 30 MHz (HF)	High-frequency radio, shortwaves. Broadcasting, amateur radio, CB.
30 MHz to 300 MHz (VHF)	Very high radio frequencies. Two-way radio, mobile, marine, aircraft, TV and FM broadcast.
300 MHz to 3 GHz (UHF) (anything above 1 GHz is called microwave)	Ultrahigh radio frequency. Two-way radio, TV broadcast, cell phones, GPS satellites, wireless broadband, wireless networks.
3 GHz to 30 GHz (EHF)	Extremely high radio frequencies. Radar, satellites, network radios.
30 GHz to 300 GHz	Superhigh radio frequencies. Radar, satellites, network radios, 5G cell phones.

negative) value. In Fig. 2.7B, the peak value of the sine wave (V_p) is 7 V. The peak-to-peak value, normally abbreviated V_{pp}, is the positive peak added to the negative peak. Or, since the positive and negative peaks are identical in a sine wave, the peak-to-peak value is two times the peak value, or in this case 14 V.

$$V_{pp} = 2V_p$$

Another way to measure AC voltage is to use an average value known as rms or effective value. The rms value is computed by multiplying the peak value by 0.707 or:

$$V_{rms} = 0.707V_p$$

Thus, the rms value of the sine wave is $0.707 \times 7 = 4.949$ V. Most sine wave voltages are measured and stated in terms of rms value. The amount of AC voltage available at a standard AC outlet, for example, is $120 V_{rms}$. The rms value, as discussed above, is applied only to sine waves. The significance of the rms value is discussed later when we address power.

PRACTICAL DIRECT CURRENT AND ALTERNATING CURRENT VOLTAGE SOURCES

Just what is the source of DC and AC? Such voltages originate from a variety of sources.

Direct Current Voltage Sources

Batteries

The most common source of DC voltage is a battery. A battery is a collection of cells. A cell is the basic unit of voltage generation that creates electricity by chemical action. A battery is made up of two or more cells connected together. Fig. 2.8

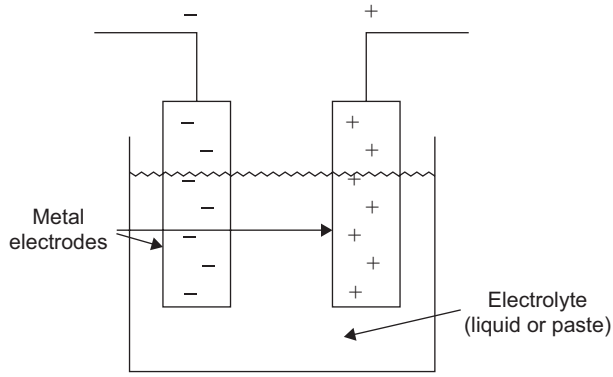


FIGURE 2.8 Basic concept of any battery.

TABLE 2.2 Most Popular Types of Cells/Batteries and Typical Applications

Materials	Voltage	Type	Applications
Alkaline	1.5	Primary	AAA, AA, C, D cells; flashlights; toys; and much more
Mercuric oxide	1.35	Primary	Watches; calculators
Silver oxide	1.6	Primary	Hearing aids; watches
Nickel–cadmium	1.2	Secondary	Tools
Nickel metal hydride	1.2	Secondary	Laptops; cell phones; power tools
Lead acid	2.1	Secondary	Cars; golf carts
Lithium ion	4.1	Secondary	Cell phones; tablets; laptops; electric cars

shows the configuration of a cell. It consists of two metal electrodes immersed in a solution called an electrolyte. The chemical interaction between the metal electrodes and the electrolyte produces a separation of charges. This separation of charges results in an excess of electrons on one electrode (the − terminal of the cell) and a shortage of electrons on the other electrode (the + terminal of the cell). If a conductor is connected externally between the terminals, electrons will flow from − to +.

The amount of voltage produced by the cell depends on the type of electrodes and the electrolyte. Various chemical combinations generate different voltages. Table 2.2 lists the most commonly used cells and the voltage they generate.

The schematic symbol of a cell is illustrated in Fig. 2.9A. To create a battery, two or more cells are connected together. The cells are usually connected in series form, that is, end to end and − to +, as shown in Fig. 2.9B. The cell voltages add up to produce the total battery voltage. For example, six small alkaline cells are connected in series to create a $1.5 \times 6 = 9$-V transistor radio battery. A car battery consists of six lead–acid cells connected in series; each produces 2.1 V for a total battery voltage of $6 \times 2.1 = 12.6$ V. If four nickel metal hydride cells are connected in series, as in Fig. 2.9B, the total battery voltage is 4.8 V.

The simplified schematic symbol for a battery is shown in Fig. 2.9C. Instead of drawing all of the individual cells, the simplified battery symbol is used.

The cells listed in Table 2.2 can be separated into two categories, primary and secondary. *Primary cells* cannot be recharged. As the chemical action

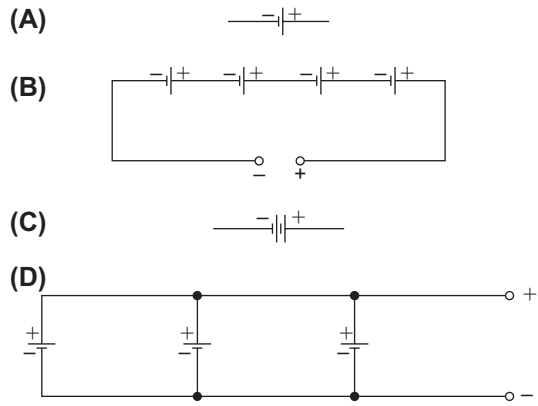


FIGURE 2.9 Battery and cell symbols used in circuit diagrams. (A) Cell. (B) Four cells in series making a battery. Cell voltage add-up. (C) Symbol for battery of any number of cells. (D) Cells in parallel to increase current capability.

produces voltage, the electrodes and electrolyte are actually used up. At some point, no further chemical action is produced, and no voltage is generated. The cell must be discarded and replaced.

Secondary cells, on the other hand, can be recharged. In these cells, the chemical action can be reversed by connecting an external DC voltage to the battery. This is called *charging*. Charging forces electrons into the battery, producing a reverse chemical action that rejuvenates the electrodes and the electrolyte. The cell can be discharged and charged repeatedly, giving it a very long life.

The amount of current that can be drawn from a cell depends on its size and the quantity of the materials used. Large electrodes and electrolytes can produce more current, but the voltage stays the same; the type of material, not its volume, determines voltage.

For example, a large D-size flashlight cell and a tiny AAA penlight cell are both made of alkaline material so their output voltages are both 1.5 V. The D-cell, however, can produce more current and will have a longer life because it is larger.

A greater current capacity can be obtained by simply connecting two or more cells in parallel. In a parallel connection, the cells are wired across one another, all + leads connected together, and all − leads connected together, as shown in Fig. 2.9D. The output voltage remains the same, but the current output can be higher.

Solar Cells

A special type of voltage-producing cell is the so-called *solar cell*. Also called a *photovoltaic* cell, a solar cell converts light into electrical energy.

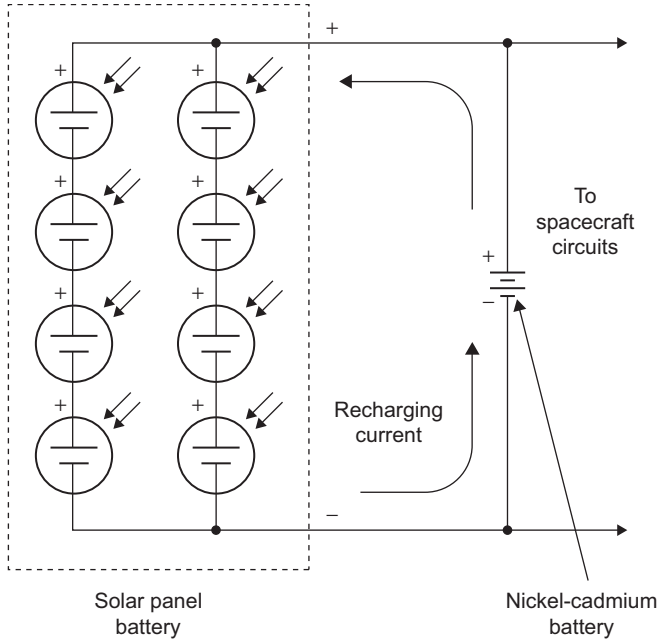


FIGURE 2.10 Panel comprised of solar cells in series and parallel make up DC source that charges the battery in a spacecraft.

When the sun or artificial light shines on the cell surface, a voltage is generated. The most commonly used material is silicon, and a typical cell generates about 0.5 V. Other materials, such as cadmium sulfide and gallium arsenide, are also used.

You have probably seen solar cells used in handheld calculators. Big arrays of solar cells are now being adopted as an energy source for homes and businesses. Another important application is spacecraft. Virtually every satellite, deep-space probe or other space vehicle, uses solar cells for power. Huge panels of solar cells connected in a complex series–parallel array produce a powerful battery that can operate all electrical and electronic equipment on board. Typically, however, such a solar battery is primarily used to recharge the main spacecraft power source, which may be a nickel–cadmium secondary battery, as shown in Fig. 2.10. The voltage produced by this array is 2 V.

Fuel Cell

A fuel cell is a special type of battery that combines oxygen and hydrogen gas to produce voltage and electron flow. That means you have to have a supply of hydrogen gas, which is usually stored in a bottle or other container. Typically,

the oxygen can be extracted from the air, but if not you will need a bottle of oxygen as well. When you combine the two, charges separate and plus (+) and minus (−) terminals are formed. Most fuel cells generate between 0.5 V and 0.9 V, so you have to put many of them in series to be useful. Usually they are bulky and inconvenient because of the need for the gases. But as long as oxygen and hydrogen are supplied, the fuel cell produces the voltage. Heat and water are by-products of the chemical process, making them essentially impractical for many applications.

Power Supplies

Electronic circuits require a source of DC for proper operation. A great many electronic products are still powered by batteries because they are small and portable, such as cell phones, iPods, and the like. Other electronic equipment is designed to operate from the AC power line. Such equipment contains an electronic power supply that converts AC into the required DC voltages. Computers, TV sets, and other nonportable electronic equipment have an AC power supply.

Alternating Current Voltage Sources

Generators

The AC that appears at the outlets of our homes and offices is produced by huge electromechanical generators owned and operated by an electrical utility company. A source of mechanical power—such as water, or a steam turbine powered by oil, coal, or nuclear fuel—operates the generator. The turbine converts steam into mechanical energy to turn the generator. The generator rotates coils in a strong magnetic field to produce a voltage. The speed of rotation of the coils determines the frequency. That voltage is a 60-Hz sine wave.

The big wind generators popping up across the landscape also produce AC sine waves, but because the rotational speed depends on the wind speed, the AC frequency will vary, which is unacceptable. Therefore, the AC voltage they produce is converted to DC, and then back into AC of the correct frequency (60 Hz) to be used or put on the AC power grid.

Another example is the alternator in your car. "Alternator" is just another word for an AC generator. The alternator, driven by the car engine through a belt, produces AC output that is converted to DC by diodes making up a rectifier. The rectifier output is DC to charge the battery.

Inverters

Electronic circuits called inverters are used to produce AC from a DC source. This is common in solar power systems. The solar cells produce DC, which keeps batteries charged. The DC is then converted to AC by the inverter.

In electronic equipment, AC signals are generated by circuits called *oscillators* or *function generators*. The AC signals are sine waves, square (rectangular) waves, or triangular waves, among others.

Analog and Digital Signals

You have no doubt heard the terms "analog" and "digital." These terms distinguish between the two main types of voltages or signals in electronic equipment. Analog signals are voltages that vary smoothly and continuously over time. You saw some in previous figures. Analog signals may be either DC or AC. A continuous DC voltage is analog, as well as a varying DC signal. A sine wave and the random signal in Fig. 2.7E are also analog signals.

Analog signals come from microphones, video cameras, and sensors that detect light level, temperature, and other physical conditions. The most common types of analog signals are voice or music from a microphone and video from a camera.

Digital signals are pulses or on–off signals. The DC pulses in Fig. 2.6E and 2.7 are digital. Most digital signals are binary in nature, meaning they only have two voltage values. In Fig. 2.6E the two values of voltage are 112 and 0 V. In Fig. 2.7C the two voltage levels are 13 and 23 V.

You will see both analog and digital signals in all sectors of electronics. Today, most signals are digital. Special circuits called analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) are used to translate between the two types of signals.

Fourier Theory and the Frequency Domain

We normally think of electronic signals as voltages that vary over time. Waveforms showing signals are said to be in the time domain. Time is the horizontal axis in a graph. But there is another way to look at signals in the frequency domain where frequency is on the horizontal axis. For example, a sine wave is shown as a single vertical line at its frequency as Fig. 2.11A shows. The height of the line is representative of the voltage level, either peak or rms.

The big question is: how do you show a complex signal like a square wave in the frequency domain? The only way to do this is to use the Fourier theory that says that any complex nonsinusoidal wave is made up of a group of sine waves added together. There is a fundamental sine wave that occurs at the signal frequency plus harmonic sine waves. A harmonic is a sine wave whose frequency is an integer (whole number) multiple of the fundamental sine wave. The second harmonic of a 50-MHz sine wave is a 100-MHz sine wave. The third harmonic is a 150-MHz sine wave and so on. If you add the fundamental sine wave to multiple harmonics of differing amplitudes and phases, you can create any shape of wave.

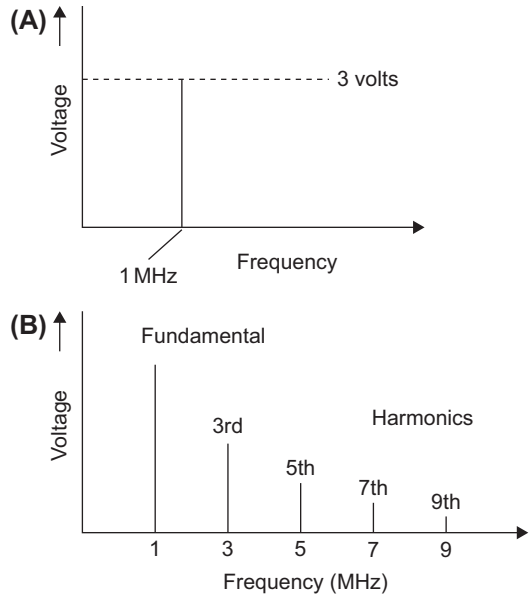


FIGURE 2.11 Frequency-domain views. (A) 1-MHz sine wave. (B) 1-MHz square wave.

For instance, a square wave is made up of a fundamental sine wave and all the odd harmonics. A 1-MHz square wave is made up of a fundamental 1-MHz sine wave and harmonics of 3 MHz, 5 MHz, 7 MHz, and so on. According to Fourier theory, it takes an infinite number of harmonics but in reality only a few (like up to the fifth or seventh) are needed to approximate the square wave. The frequency domain plot of a square wave therefore would look like the one in Fig. 2.11B.

When looking at a time domain view of a signal, try to keep a frequency-domain picture in mind at the same time. You cannot actually see the third or fifth harmonics in the time domain plot but they are buried in there just the same.

Project 2.1

Getting Familiar With a Multimeter

One of the things you are going to need as you work with electronic parts, circuits, and equipment is a multimeter. This is a test instrument that measures voltage, current, and resistance. Some also measure capacitance and other things. These multimeters are usually handheld and battery operated. There are two basic types, analog and digital. Analog meters use a dial to show the measured value. Digital multimeters (DMMs) have a liquid crystal display (LCD) to show the measurement. See Fig. 2.12. The two types work equally well; which one you use is typically a matter of preference for meters versus digital displays. I recommend a digital unit.

Continued

Project 2.1—cont'd

FIGURE 2.12 A low cost digital multimeter that measures DC and AC voltages, current, and resistance.

The good news is that multimeters are not expensive. You can get one for as little as $10, but a better unit may cost you several times that. The cheaper units are kits that you will need to build yourself. I do not recommend a kit if you are just starting out. Later in this book, I will discuss kits in more detail. In any case, you need to buy a multimeter and learn to use it. Plan to buy one as soon as you can.

Several good sources of multimeters are as follows:

Adafruit: www.adafruit.com
Elenco Electronics: www.elenco.com
Fry's: www.frys.com
Jameco: www.jameco.com
Kelvin Electronics: www.kelvin.com
SparkFun: www.sparkfun.com
Velleman: www.velleman.com
Ask for a printed catalog when you inquire.

Project 2.2

Hardware Sources

As an electronic experimenter, you should be familiar with buying parts and equipment. RadioShack stores still stock some parts, but today most hobbyists and experimenters buy via the mail or online. The most popular sources of parts and equipment are All Electronics, Digi-Key, Mouser, and Jameco. And you will discover others. You can go to their websites, but you really should get on their mailing list and get a catalog. Do that as soon as you can. Links to these sources are given below. You can get your multimeter from one of them as well.

Adafruit: www.adafruit.com
All Electronics: www.allelectronics.com
Digi-Key: http://www.digikey.com
Jameco: http://www.jameco.com
Mouser: www.mouser.com
SparkFun: www.sparkfun.com

Project 2.3

Magazines of Interest

As you are learning electronics, you need to be continuously aware of what is going on in the industry and with the technology. Magazines are a good source of that information. One that you should read on a regular basis is *Nuts & Volts*. It is available at some newsstands and bookstores, but if you cannot locate it, go to the website and subscribe. This magazine has lots of articles and columns, including construction projects. It is a great way to stay up to date and learn more. *Nuts & Volts* also publishes *Servo* magazine, which is aimed at people who like to build and play around with robots.

Another recommended magazine that has an embedded controller emphasis is *Circuit Cellar*. This publication contains great educational articles and projects. Get a subscription if you are serious about learning more.

Another interesting magazine is called *Make*—it is not strictly electronics but it usually contains some good electronic projects. It also features other mechanical projects such as robots, among other things. This one is definitely worth a look the next time you are at the newsstand.

Nuts & Volts and *Servo*: www.nutsvolts.com
Circuit Cellar: www.circuitcellar.com
Make: www.makezine.com

Project 2.4

Measuring Voltages

A good first step in using a multimeter is to measure voltages. Batteries are a good place to start. Look around the house and locate some batteries that you commonly use. Take them out of the equipment before you measure them. You will most likely find AA or C cells. Set the multimeter to measure DC according to the meter user's manual and connect the test leads to the battery. The red lead is + and the black lead is −. The LCD on the meter should show the voltage. It should be 1.5V. You can also check batteries in some cordless phones, cell phones, or other devices. You may be able to remove the battery from a laptop. In each case, check to determine the battery technology—lithium ion, alkaline, and so on.

Two key points to remember: first, if you get the test leads reversed, the red to the − terminal of the battery and the black to the + terminal, the meter will read a negative value. That just means that the leads are reversed, nothing more. Second, you cannot typically judge the condition of the battery by measuring its voltage. With no load on the battery, no current is drawn from it so you are just measuring the characteristic voltage. If you connect the battery to something, current will flow and its voltage will decrease slightly. If it decreases a lot, the battery is going bad. If the cell or battery voltage is several tenths of a volt lower than the characteristic value given in Table 2.2, the battery is probably bad.

Continued

Project 2.4—cont'd

You could also go out to your car and measure its battery voltage. Be careful. You cannot get shocked but you could short something. When the engine is off, the battery will probably register about 12V. With the engine running, the battery voltage will be a bit higher, as much as 15V or so. The generator is charging the battery, making its voltage a bit higher.

One last thing: You can use the multimeter to measure the AC line voltage at an outlet. Only do this if you have probes that will fit into the slots on the outlet.

And be supercareful as you can kill yourself. Be paranoid, even.

Set the multimeter for AC voltage at an appropriate level of at least 120V, according to the multimeter manual. Place the probe tips into the AC outlet and read the voltage.

Do not touch any metal with the probe tips!!

Your value will depend on things like how far you are from the power station, what appliances and other items are on, and time of day. In any case, the voltage range is about 95–130V. It is rarely lower than 110 or higher than 125V. The typical value is 120V, or what is called *nominal*. I measured mine at 117V.

Project 2.5

Build a Simple Solar Electrical System

Most electronic equipment is a system, a collection of parts, components, modules, and subassemblies. The system receives electrical or electronic inputs, processes them, and generates useful new outputs. An example is a solar power system similar to one that may be used in some homes.

Refer to Fig. 2.13. A solar panel battery receives energy from the Sun to generate a DC voltage. This voltage is used to maintain a charge on a battery. A charge controller keeps the battery from overcharging and develops the output voltage to the inverter. The battery then powers a DC to AC inverter. The inverter generates a 60 Hz AC voltage at the common line voltage of 120V. Any standard load such as a lamp or radio can be plugged in to operate from the inverter. In this project, you will build and operate such a system.

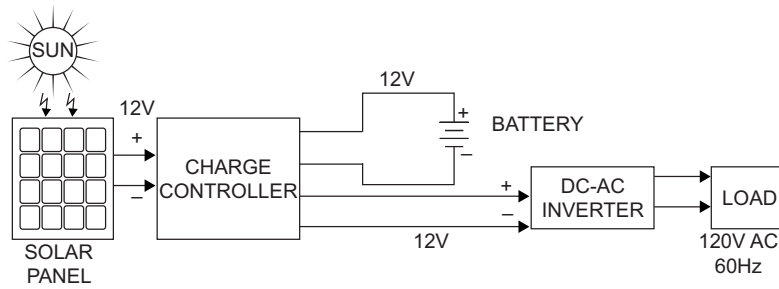


FIGURE 2.13 A simple solar power system.

Project 2.5—cont'd

- First acquire the parts. These are listed in Appendix B parts list. I got mine from All Electronics and the inverter came from a local Best Buy. There are other sources.
- Before you build the system, take the solar panel outside in the sun and measure its output voltage with your DMM. In direct sunlight a 12V panel has a no-load, open circuit output of between 16 and 20V. When you connect a load, the output will drop to its approximate nominal 12 V value.
- Assemble the parts as shown in Fig. 2.13. Follow the wiring directions given for the charge controller. This device manages the charging of the battery to prevent overcharging and damage and conditions the battery output to the inverter. Be sure to observe the polarity of each connection! The inverter usually comes with a 12V lighter plug like those used in cars. You may wish to use clip leads to make the connections faster and easier. Fig. 2.14 shows a photo of a typical system. Clip leads were used on some of the connections.

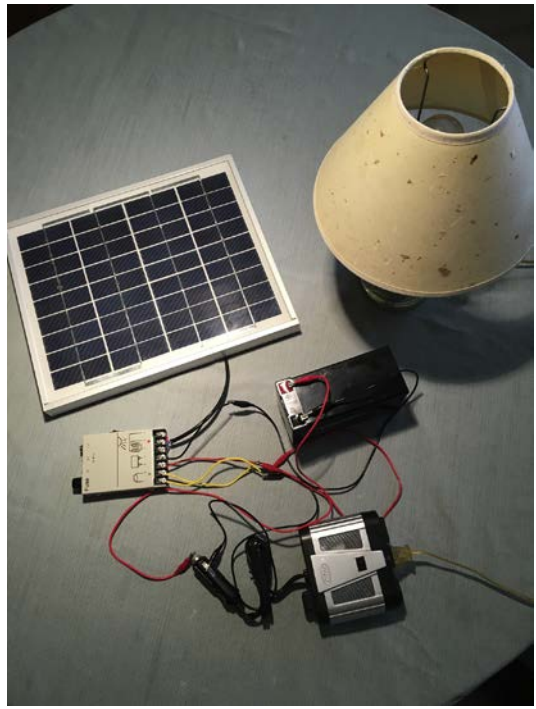


FIGURE 2.14 An experimental solar power system. The solar panel feeds the charge controller below the panel. The charge controller connects to and charges the black battery on the right. The other charge controller output connects to the inverter below. The lamp plugs into the inverter. Clip leads are used to make the temporary connections.

- Connect a load to the inverter. I used a small table lamp and plugged it into one of the inverter's normal AC outlets. Be sure the wattage of the lamp does not exceed the wattage capacity of the inverter.

Continued

Project 2.5—cont'd

- The battery should have an initial charge on it, but check it with your DMM to see that its output is about 12V or more.
- Take the system outside and let the sun charge the battery. The charge controller may have an off–on switch so turn it on if it does. Let the battery charge for about an hour.
- With all but the load turned on, use the DMM to measure the charge controller inputs and outputs to see if all are present. They should all be about 12V or so.
- Test your load. Turn on the lamp. It should work as normal.
- Use your DMM to measure the AC output voltage at the inverter outlet. Set your DMM to the AC mode and be very careful as the 120V output can severely shock you. You should measure about 120V.
- Turn off everything and disconnect the battery.

Chapter 3

The Systems Versus Components View of Electronics

A Fresh New Way to Learn About Electronics

In this Chapter:

- Systems defined.
- Examples of systems.
- Introduction to basic electronic components.

INTRODUCTION

When learning about electronics in the past, you started with basics of physics and math, and then went on to learn electrical theories. Next came instruction in how electronic components work, and then you combined them into circuits. Then you put the circuits together into specific pieces of equipment. Finally, knowing the equipment, you could understand the application, such as TV or computers, audio or home system control, or whatever. This approach to learning is called the bottom-up approach. You learned the details and added them all together to get to what you really wanted to know about—the application and its technology.

That is still the way you learn electronics in college today, and it is the approach taken by most other electronics books you may have seen. This book does not take that old legacy path. Instead, it skips most of the early background and theory, goes right for details on the circuits, and then builds to the applications. It is a much more interesting way to learn electronics. And it is also far more relevant to how electronic equipment is implemented today. We call this way of learning the "systems view" of electronics.

WHY SYSTEMS AND NOT CIRCUITS?

What is the advantage of this approach? First, thanks to modern semiconductor technology, most electronic components and circuits are inside chips or integrated circuits (ICs). You cannot see them, and you cannot access, test, or

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00003-5
Copyright © 2018 Elsevier Inc. All rights reserved.

replace them. About all you can do is to learn what they do and then work with the various input and output signals. Since you do not have access to the components and circuits, there is some argument as to why you need to learn all that circuit theory detail. If you are an engineer designing ICs, you definitely need to know this. Otherwise, it is just a waste of time unless you want to know just for the heck of it. Some of it is nice to know, of course, but in most cases it is not necessary. What you really need to know is what the circuit is, what it does, what its characteristics are, and what the inputs and outputs should look like.

A good example is the power supply in a PC. If it goes bad, you just replace it with a $30 unit that you can buy online. Troubleshooting the power supply would take many hours and require some expensive test equipment and access to spare parts. The whole repair could take hours and at a typical rate of, say, $50/h, or more, it could cost hundreds of dollars and take weeks to get the new parts. A quick replacement with the $30 unit takes only about a half hour at most. So for less time and money, you get your PC working faster. Not a bad deal at all.

A cell phone is the same. It takes hours of troubleshooting and very expensive test equipment to troubleshoot and repair one. A typical repair would cost hundreds of dollars. Consequently, it is rarely done. It is sometimes cheaper to get a new cell phone, and it will be a better one at that. And it may even be free if you renew your service contract. That is electronics today.

The ability to analyze circuit operation by tracing electron flow through the various components used to be necessary. That made it necessary to know about all the components in detail and how they all come together to make a circuit. But with the systems view, you rarely need this knowledge unless you are an engineer designing the circuits or the equipment. In most cases you are not, so why invest the time?

The systems view is a better approach, as you do learn about the circuits and the equipment at a higher level. Later, if you want or need to, you can delve deeper into the circuit and component details, just for fun or to satisfy your curiosity. We will not do that in this book. But you will get the system view and big picture that will serve you well in learning electronics.

The systems view is more important today because ICs have made it possible to largely ignore the internal details. The ICs and systems on a chip (SoC) have resulted in the throwaway electronics society in which we live. It is no longer possible or economical to repair most electronic equipment, thanks to ICs. The cost of labor, the cost of test instruments to troubleshoot equipment, and the difficulty of replacing ICs have made it more practical to just discard a bad piece of electronic equipment rather than repair it. It costs less and you get a newer and better replacement product as a result. Not a bad deal.

Yes, it is still possible to repair some equipment. For example, big expensive equipment such as a magnetic resonance imaging (MRI) machine is usually repairable; however, it is not done by replacing bad components, but by

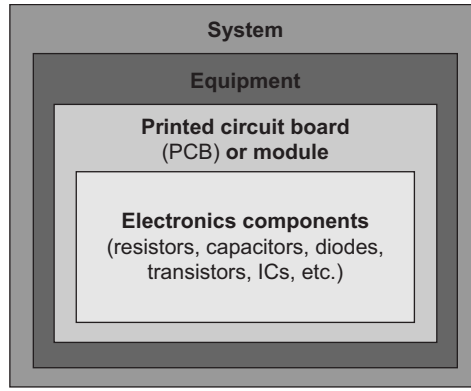


FIGURE 3.1 Hierarchy of electronics from systems to components.

replacing defective modules, subassemblies, or printed circuit boards (PCBs). You do not have to know how to analyze circuits to do that. You just troubleshoot by observing signal flow, measuring inputs and outputs, and replacing any module or subassembly that does not work. You get the equipment working sooner and at lower cost.

A good way to picture the systems view is shown in Fig. 3.1. It all begins with the components that make up the circuits that in turn make up the modules and subassemblies, usually on PCBs. Those are put together to form pieces of equipment. Finally, multiple pieces of equipment may end up being interconnected to form some kind of system. A few system examples will show you the idea.

A personal computer (PC) is a great example of a system (see Fig. 3.2). It is made up of modules including a motherboard with its processor, memory ICs, and input/output (I/O) interfaces. There is a power supply module, a hard disk drive, a CD/DVD drive, and perhaps a video card. Then the system is completed when it is connected to the video monitor, keyboard, mouse, printer, and Internet modem.

A consumer home entertainment system is made up of a big-screen HDTV set, a cable or satellite box, a DVD/Blu-ray player, and an audio amplifier/receiver with speakers. Other equipment may be involved such as an over-the-top Internet TV connection with a Wi-Fi unit from Apple TV or Roku. The TV itself or any of the other components are systems in their own right.

An iPod or MP3 player is a simple system. Shown in Fig. 3.3, it consists of a memory, either a solid-state flash memory that stores the music, an audio codec IC that does the digital music decompression, digital-to-analog conversion and analog-to-digital conversion for storing music, a microcontroller that controls the whole thing including the selection controls, and the LCD readout. A pair of audio amplifiers and a headset complete the system. A power management system charges the battery and doles out DC to power the various ICs.

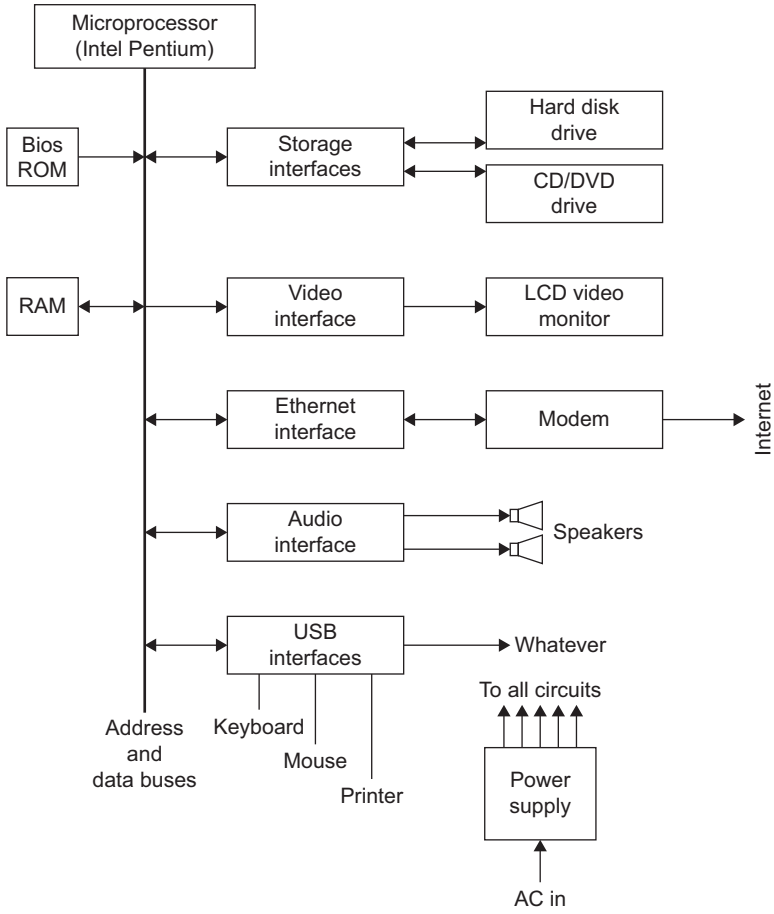


FIGURE 3.2 System block diagram of typical personal computer.

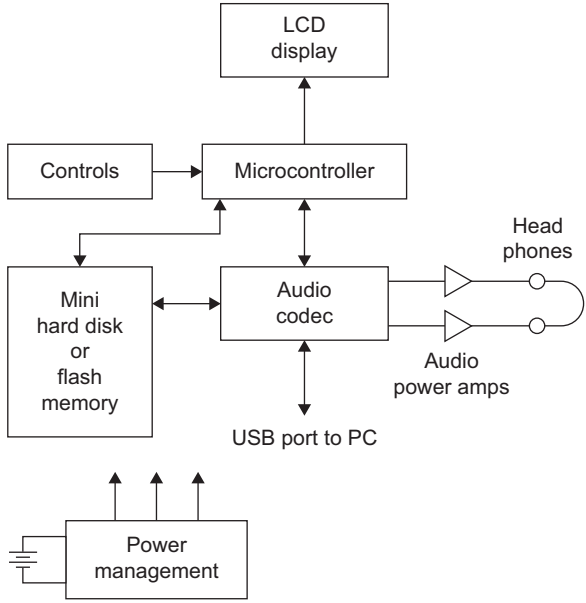


FIGURE 3.3 System block diagram of iPod or MP3 music player.

An MRI machine is a whole system. It is made up of the central bed surrounded by a superconducting magnet and radio frequency–sensing coils, high-power radio frequency (RF) amplifiers and detectors, the video imaging section, and a computer that runs the whole thing.

Anyway, you get the picture. There are big systems, little systems, and lots of in-between systems. Their main characteristic today is that you cannot get at the individual components and circuits, but there are exceptions.

In this book we look mainly at the circuits, equipment, and systems, not the components. We will give you a quickie introduction to the main components but move on to the circuits and systems.

ELECTRONIC COMPONENTS

Most systems today are collections of ICs wired together on PCBs and packaged in a housing of some sort. The MP3 player/iPod in Fig. 3.3 is a great example. Each block in that diagram is an IC. In the past, systems were made with PCBs and other assemblies, but the circuits were made with discrete components, individual resistors, capacitors, diodes, transistors, and even some ICs. You will still see these here and there in modern equipment; just remember that most circuits and equipment are just a batch of ICs.

Just so you will not be ignorant of components, here is a nutshell introduction that should serve you well when learning electronics the system way. If you want to dig deeper, you can find many other books that will make your eyes glaze over with detail.

Switches

There is no simpler electrical component than a switch. It is just two (sometimes more) metal contacts and a mechanical device to open and close them. In one position the switch contacts are open and not touching so that no current will flow through them; the switch is "off." Moving the switch lever, the contacts are made to touch making a path for current to flow; the switch is said to be "on."

Fig. 3.4 shows a switch in a circuit diagram called a *schematic*. This shows the switch connected to a battery and a light-emitting diode (LED) in a simple flashlight. The other component is a resistor to limit the current.

Resistors

Resistors are one of the most common components in electronics. These devices offer opposition to current flow; they limit or set the level of current in a circuit. The opposition to current flow is measured in ohms. The higher the ohms value, the more resistance it offers to electron flow.

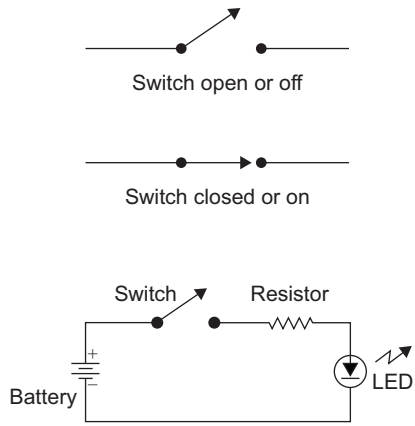


FIGURE 3.4 Switch and how it is used.

Ohm's Law

There is one key electrical relationship you should know, called Ohm's law. It is simple and easy to understand. It says the current in a circuit (I) is directly proportional to the voltage (V) and inversely to the resistance (R). It is usually expressed as a simple formula:

$$I = V/R$$

If you increase the voltage in a given resistance, the current increases. That makes sense since the voltage charge simply attracts and repels more electrons. Increasing the resistance makes the current decrease. Since resistance opposes current flow, more resistance with the same voltage will make the current decrease.

Keep this simple relationship in mind, as it is the heart of every electrical and electronic application.

Today most resistors are made along with all the other circuitries in an IC. But discrete component resistors are also still fairly widely used. The most common ones are called chip resistors and look something like the one shown in Fig. 3.5. They are small and you can just make them out when looking at a PCB. Older but still used resistors are cylindrical like the one shown in Fig. 3.5. The schematic symbol used to represent a resistor in a schematic diagram is shown in Fig. 3.5. Color-coded resistors use a set of color bands with a special code to indicate their value (see Fig. 3.6).

An example of a common resistor circuit is the voltage divider shown in Fig. 3.7. It is used to attenuate a voltage or signal or make it lower. The two resistors of the voltage divider are connected in series. When current flows, a voltage develops across the two resistors. The input voltage is divided between the two resistors according to their value. In any case, the output is taken from one of the resistors and it is lower in value than the input.

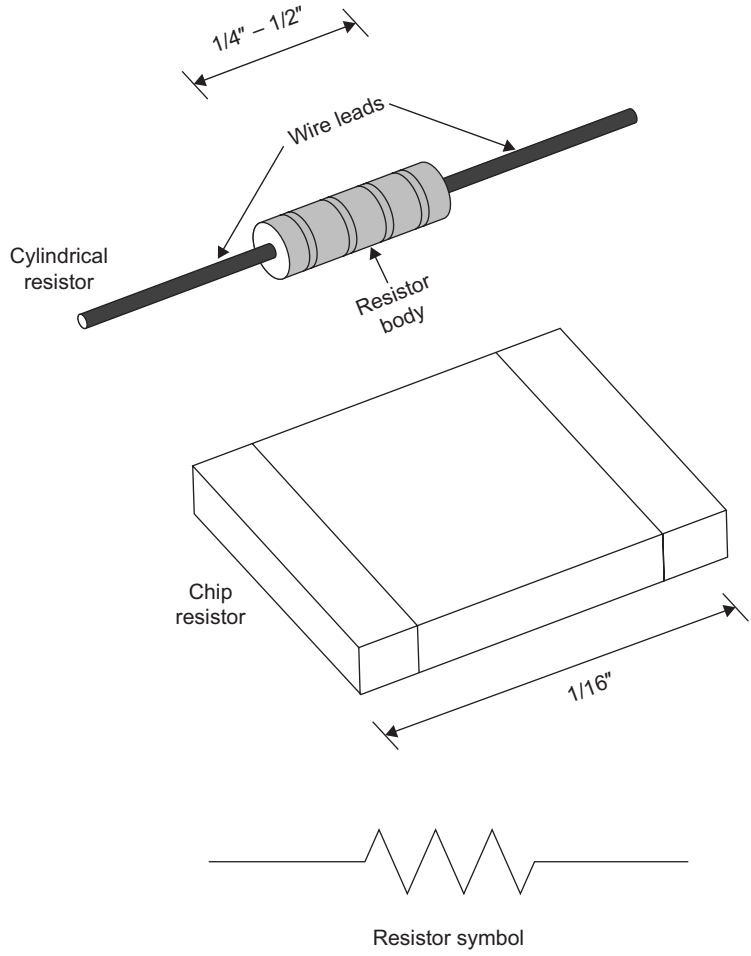
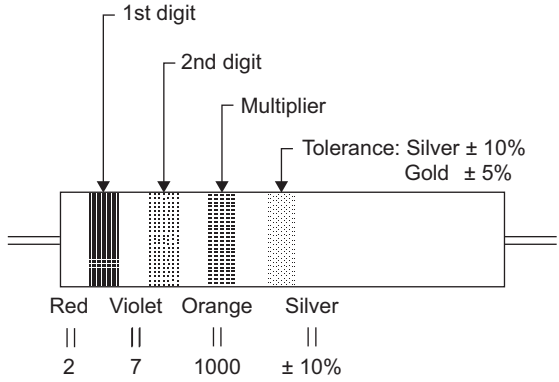


FIGURE 3.5 Types of resistors and schematic symbol.

Capacitors

A capacitor is a device that stores electrical charge. It is made up of two metallic plates separated by an insulator such as plastic or ceramic or even air (see Fig. 3.8). The symbol for a capacitor in schematics is also shown.

The basic function of a capacitor is to be charged or discharged. You charge the capacitor by applying a voltage to it as shown in Fig. 3.9A. The electrons pile up on one plate making it negative and are pulled away from the other plate making it positive. It takes a finite amount of time for the capacitor to charge as determined by the values of capacitance (C), stated in farads (F), and resistance (R). That time is called the time constant (T). In the charged state, the capacitor stores the voltage. The capacitor in its charged state is almost like a battery, as it can supply DC voltage to a circuit or load.



Value: 27,000 Ohms ± 10%

Resistor color code

Color of band	Value	Multiplier
Black	0	1
Brown	1	10
Red	2	100
Orange	3	1000
Yellow	4	10,000
Green	5	100,000
Blue	6	1,000,000
Violet	7	10,000,000
Gray	8	100,000,000
White	9	1,000,000,000

FIGURE 3.6 Standard resistor color code.

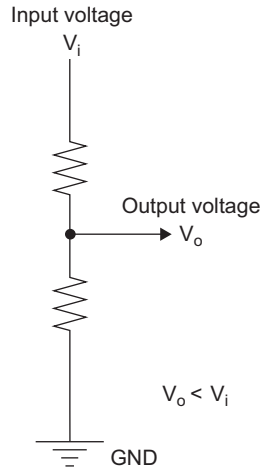


FIGURE 3.7 Voltage divider, the most common resistor circuit.

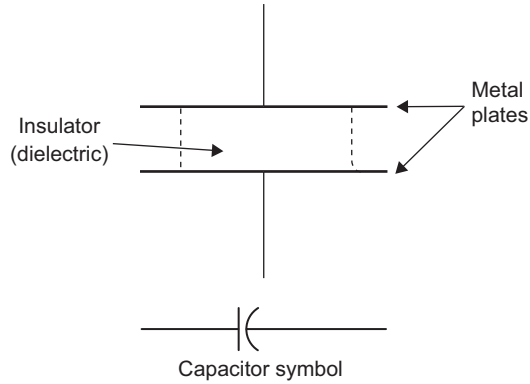


FIGURE 3.8 Capacitor construction and schematic symbol.

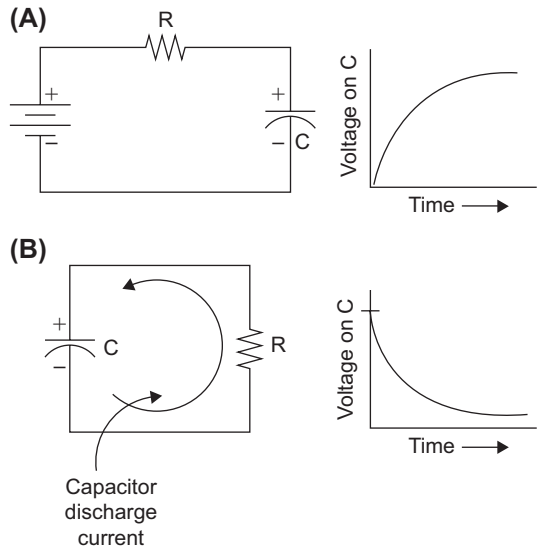


FIGURE 3.9 (A) Charging capacitor, (B) discharging capacitor.

The energy stored in the capacitor is used by discharging it into a load such as a resistor (see Fig. 3.9B). The electrons then flow from the negative plate through the resistor to the positive plate. Current flows until the charge is dissipated. Again, it takes time for the discharge to occur.

When capacitors are used with AC signals, they offer opposition to current flow called *capacitive reactance*. It is like resistance in that it determines current flow, but it varies with the frequency of the AC and capacitor value.

Capacitors perform all sorts of functions in electronic circuits. They are used for filtering and to pass AC but block DC. Fig. 3.10 shows a low-pass filter

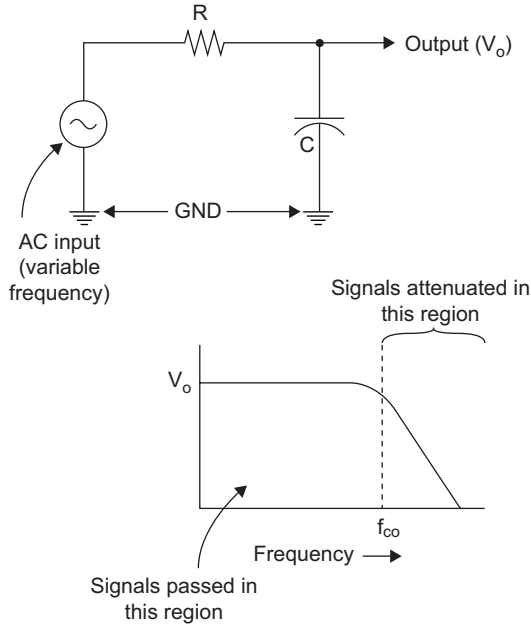


FIGURE 3.10 Low-pass filter, a common capacitor use.

comprised of a resistor and a capacitor. This is a frequency-sensitive circuit that passes AC signals below a specific frequency called the *cutoff frequency* (f_{co}) and attenuates the frequencies above the cutoff. Fig. 3.11 shows how a capacitor passes AC but blocks DC.

A Word About Ground

In schematic diagrams like Fig. 3.10, you will see the triangular-shaped symbol called GND. This means ground. Ground is an electronic term that refers to a common connecting point. It may be a common wire, a metal chassis, a copper area on a PCB, or some other conductive part or area. In this figure, it means that the bottom of the AC generator and the bottom of the capacitor are connected together.

Ground is also the common reference point for measuring all voltages.

Inductors

Inductors are mainly just coils of wire. When current flows through them, they produce a magnetic field and induce a voltage in themselves. This is called *self-induction*. The induced voltage has an opposite polarity of the applied voltage. The result is that the induced voltage causes opposition to the current flow.

We often use that characteristic to control current flow in AC circuits. Like the capacitor, the inductor is an opposition to AC called *inductive reactance*. Fig. 3.12 shows the symbol of an inductor as used in schematic diagrams.

Transformers

A transformer is usually comprised of two coils or windings on a common core. The schematic symbol is shown in Fig. 3.13. A voltage applied to one winding called the *primary* causes current to flow and a magnetic field to develop. This magnetic field spreads out and induces voltage in the other winding called the

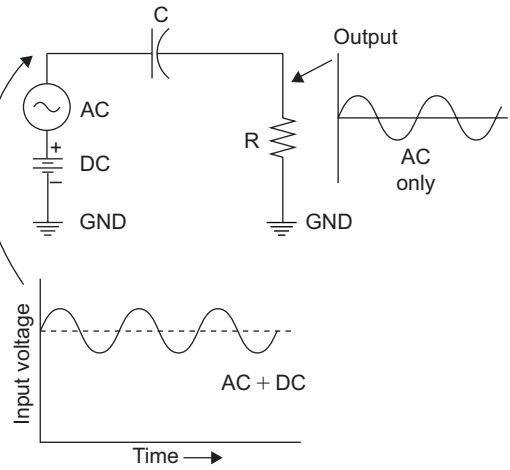


FIGURE 3.11 How capacitor passes AC sine wave but blocks DC voltage.

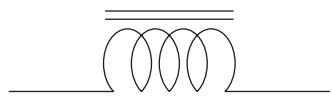


FIGURE 3.12 Schematic symbol for inductor.

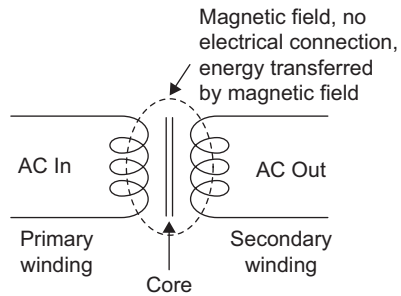


FIGURE 3.13 Schematic symbol for transformer.

secondary, thereby transferring electrical energy for one coil to another by way of the magnetic field. Transformers are used to step up or step down voltage levels of AC signals. They are also used for signal isolation as well as impedance matching.

Diodes

A diode is a semiconductor component that lets current flow through it in one direction but blocks current in the other direction depending on the polarity of the voltage applied to it. It acts like a polarity-sensitive switch. Fig. 3.14 shows a typical diode, the diode schematic symbol, and how it is biased for current or no current.

Diodes are used mainly for rectification, the process of converting AC into DC. Fig. 3.15 shows how a diode converts an AC sine wave into DC pulses. If you put a capacitor across the load resistor, it will charge up to the peak sine voltage and store it. The result is that the output is a near-constant DC value. Most electronic power supplies work like this.

Special diodes are made to emit light (LED), regulate voltage (zener diode), act as a variable capacitor (varactor), or perform as a switch (PIN diode).

Transistors

A transistor is a three-terminal semiconductor device that uses a small input signal to control a much larger output signal. One type of transistor is the bipolar

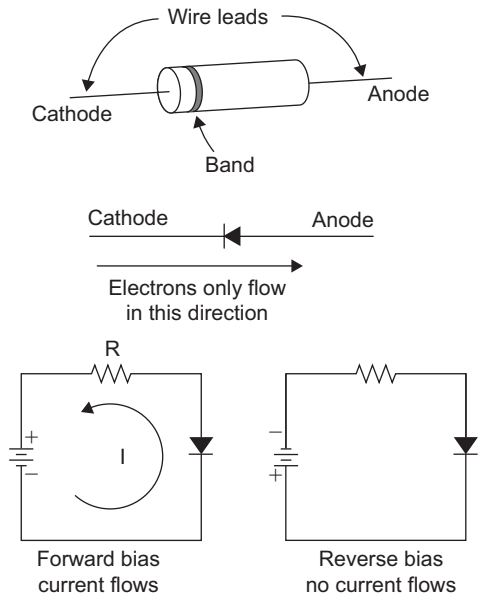


FIGURE 3.14 Diode, its schematic symbol, and how to bias it for conduction or cutoff.

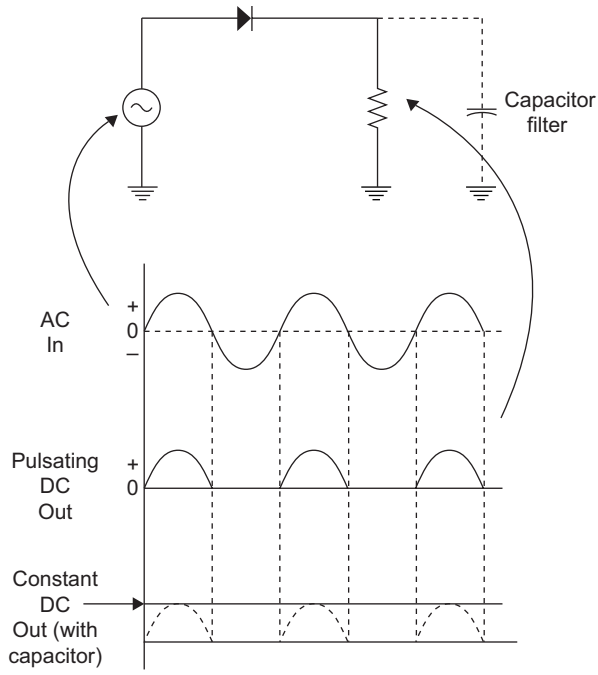


FIGURE 3.15 How a diode rectifies AC into DC.

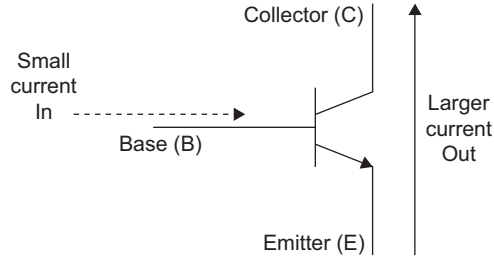


FIGURE 3.16 Schematic symbol for bipolar junction transistor (BJT) and its inputs and outputs.

junction transistor (BJT) shown in Fig. 3.16. A small current applied to the base element is used to control a larger current flowing from emitter to collector.

Another type of transistor is the metal oxide semiconductor field-effect transistor (MOSFET). It too has three elements, as shown in Fig. 3.17. A small voltage on the gate controls a larger current flowing from source to drain.

Transistors have two basic functions: amplification and switching. In amplification, the small input variation causes larger output current variation. The small input signal is not really made bigger, but the larger output variation has the same shape and characteristics, resulting in the same effect. The transistor simply varies the larger DC current from the supply and shapes it like the input.

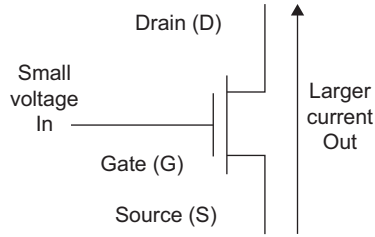


FIGURE 3.17 Schematic symbol for MOSFET and its input and outputs.

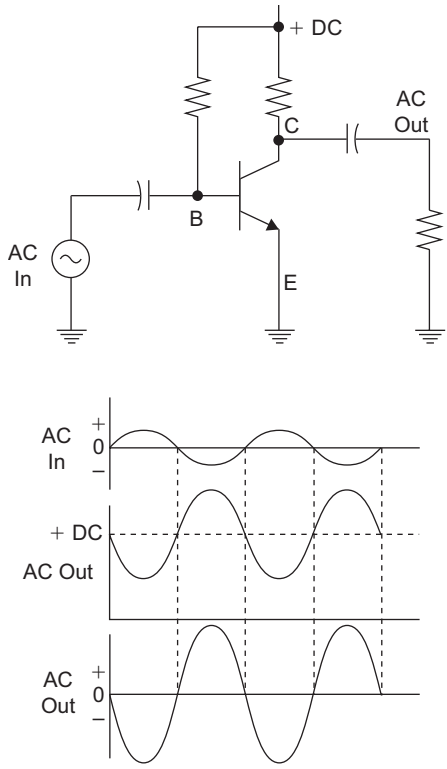


FIGURE 3.18 Simple BJT amplifier and how it works.

Amplifiers

Fig. 3.18 shows a simple BJT amplifier. The base resistor sets the base current turning the transistor on so that current flows from emitter to collector. Its output voltage is a DC value at about half the supply voltage. Now, if a small AC signal is applied through the capacitor as shown, the base current will vary. This will vary the collector current and the voltage across the collector resistor. A small variation in the base current produces a larger variation in the collector current. The output voltage is an enlarged version of the input, except that it is

reversed in phase. We say that the output is 180° out of phase with the input, called *phase inversion*. The output is a DC signal, but to convert it to AC we pass it through a capacitor to the load. All amplifiers generally work like this.

Switches

As a switch, the transistor output current is turned off or on by the smaller input current or voltage. A small input signal can switch a larger output current off and on. Switching transistors can switch very fast (in less than nanoseconds). Fig. 3.19 shows a MOSFET switch. If the input voltage on the gate is zero, the MOSFET does not conduct. It acts like an open or off switch. The output then is just the supply voltage (1 V) as seen through the resistor.

Now, if we apply voltage to the gate above a certain threshold level, the MOSFET will conduct. It acts like a closed or on switch so current flows in the resistor. The output is a very small value near zero. Fig. 3.19 also shows what the inputs and outputs look like with a square wave applied.

Integrated Circuits

An IC is also called a chip. It is a complete circuit made on a single chip of silicon. All the components are made at the same time and interconnected to form an amplifier, microcomputer, memory, oscillator, radio transceiver, or whatever the function. The IC is then connected to DC power and it works. All you do is to apply the inputs, and new outputs are produced according to what the IC function is. Most circuits today are ICs.

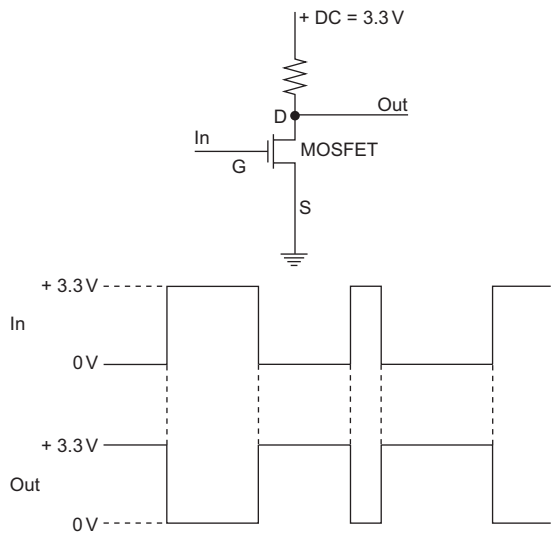


FIGURE 3.19 Simple MOSFET switch and how it works.

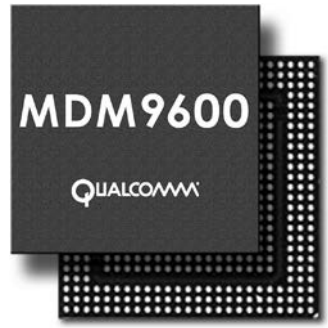


FIGURE 3.20 Typical integrated circuit today. This one is a dual-satellite TV tuner for set-top boxes. The size is only 7×7 mm. The pins are soldered to a printed circuit board. *Courtesy NXP Semiconductor.*

There are all sizes and types of ICs. There are linear circuits for analog signals, digital circuits for binary signals, and mixed signal IC for both analog and digital signals. There are small ICs that are just an amplifier or logic circuit. Then there are even larger circuits like a computer memory or a microprocessor that is the heart of every computer. Finally, there are complete SoC. Each year, it is possible to make the components on a silicon chip smaller so you can put more on a chip economically. That is why we have iPods, cell phones, and other really small devices that in the past would have been huge pieces of equipment. Fig. 3.20 is representative of ICs today.

There are lots of other electronic components but these are the main ones. A few others are introduced in later chapters.

While this book attempts to get you thinking about the big picture—the systems rather than the individual components—we cannot ignore discrete components completely. Well, actually we can, but you may be curious and want to have a bit more involvement with them. If so, the projects to follow will show you how individual parts are used. The circuits presented here are trivial compared with the sophisticated technology you use every day, such as big-screen LCD HDTV sets, laptops, cell phones, and your wireless Internet broadband router. Feel free to skip these if you wish.

Project 3.1

Setting Up a Simple Lab

If you want to play around with some components just to get the feel for how it used to be, you need to set up a simple lab. If you performed the previous projects, you already have a multimeter. Now you will need a way to interconnect parts in circuits and a power source. Appendix B is a complete parts list for the projects in each chapter.

Project 3.1—cont'd

The power source can be four AA cells in a holder. This will provide DC voltage of 6 V to power the circuits. Or you can use a common 9-V battery. A battery clip with leads will allow you to connect the 9-V battery to the circuit.

Next you will need a breadboard. This is a connector socket with multiple holes in it like that shown in Fig. 3.21. You plug the wire leads of the components into the holes to connect them to one another without soldering them.

Then you will need some components such as resistors, capacitors, and transistors. In this project, the goal is to get the battery and the breadboarding socket. The remaining projects for this chapter are circuit experiments. See Appendix B.

You can get the breadboard from a local RadioShack or from a mail order house such as Jameco. There are usually two sizes, large and small. The larger one is recommended. Fig. 3.21 shows a larger one.

Get a battery holder that will take four AA batteries. All Electronics or Jameco are good sources. Some battery holders also have an on/off switch that is useful. The battery holder may have two leads for connecting the battery to the circuit. The 9-V battery clip is shown in Fig. 3.21. You will need to solder some #22 solid copper wires to the battery clip leads as these leads use stranded wire that does not plug into breadboarding socket. Fig. 3.22 shows how. You may need to do the same thing with the AA battery holder wires. See Chapter 14 on how to solder if you need to.

Once you get the parts, put the AA cells into the holder so that you connect the negative end (–) of one battery to the positive end (+) of the next so that the cells will be in series. That way their voltages will add together. This wiring may already be present in the battery holder. The circuit should look like that in Fig. 3.23.

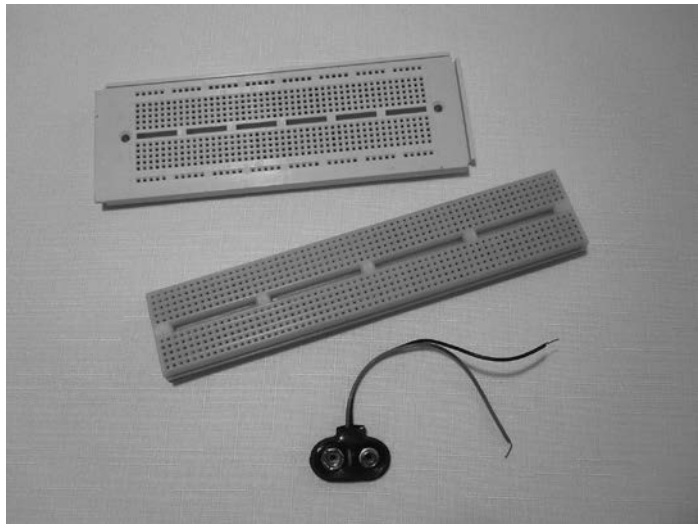


FIGURE 3.21 Common breadboarding socket for building prototypes or just experimenting. *Courtesy Global Specialties.*

Continued

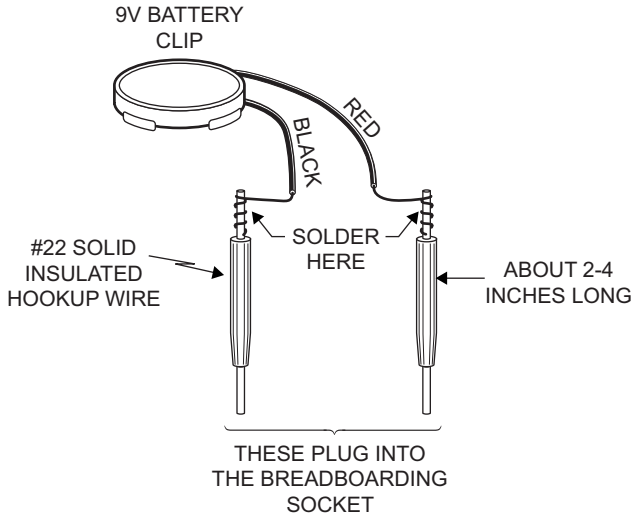


FIGURE 3.22 Soldering wires on the battery clip so they will plug into the breadboarding socket.

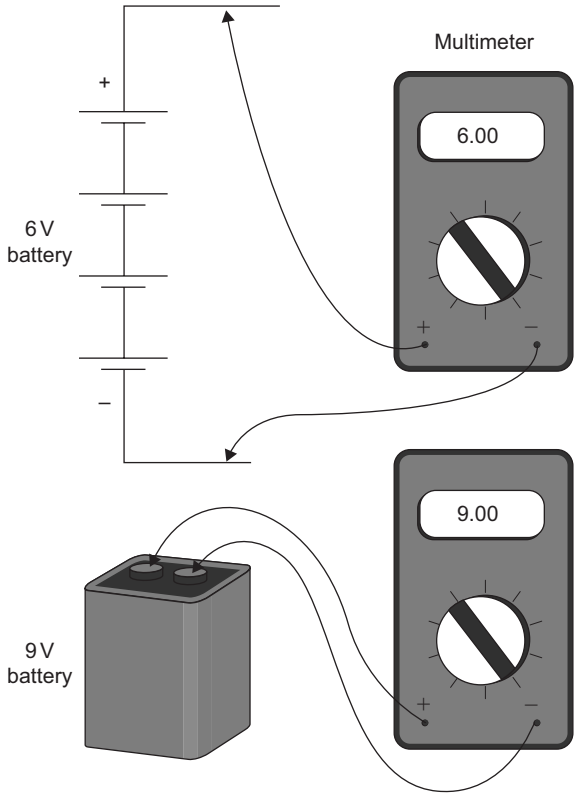


FIGURE 3.23 Measuring battery voltage with multimeter.

Project 3.1—cont'd

Next, test the battery. Using your multimeter on the DC ranges, measure the voltage across the battery holder wires. What do you get? You should read 6 V or a bit more. The 9-V battery should, of course, measure 9 V.

Now you are ready for a few additional component projects.

Project 3.2

Light-Emitting Diode

When you are buying your parts, get an LED and a set of resistors. Any old common red or green LED will work. The resistor set will be a package of all the most common values of resistors.

Now, wire up the circuit in Fig. 3.24. A pictorial is shown in the figure as well. Be sure to get the LED leads connected correctly, for if not, you will zap it. See the wiring details in the figure.

The resistor is needed to control or limit the current so that you do not blow out the LED. A value of 220 Ω is a good one if you use the 6-V battery. The color code for that resistor is red–red–brown–gold. If you are using the 9-V battery, use a 330-Ω resistor (orange–orange–brown–gold).

Wire the circuit and connect the battery. The LED should light. Now you are an electronic circuit genius.

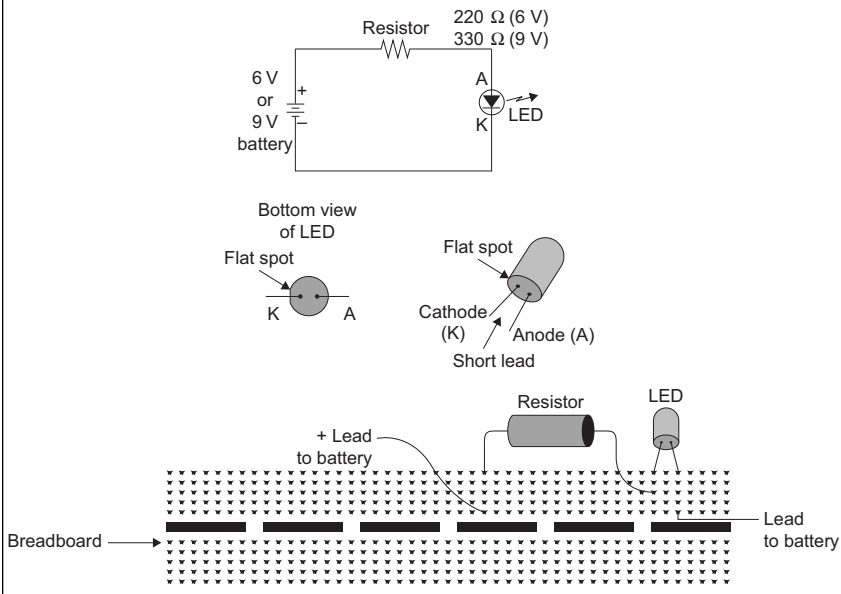


FIGURE 3.24 This is the circuit used to light an LED and how to wire it on the breadboard.

Project 3.3

Capacitors

Capacitors store a charge and then release it. The charge is stored energy. You charge the capacitor by applying a voltage to it. Then you discharge the capacitor by connecting it to a load such as a resistor. This brief project will illustrate that idea.

You will need the following parts from a parts source. Get a 100K-Ω resistor (color code brown–black–yellow–gold) and a 100-μF (microfarad) electrolytic capacitor. This capacitor is polarized, meaning that you have to observe the polarity of the voltage applied to it. The wire leads are usually marked with either a + sign, or sometimes with a – sign.

Wire the circuit shown in Fig. 3.25 on the breadboarding socket. Check the capacitor lead polarity. Do not initially connect the positive lead of the battery to the resistor. Connect your multimeter across the capacitor. Now connect the 6 V (or 9 V) from the battery supply as indicated when you are ready to start charging the capacitor. You should see the voltage begin to rise slowly. It should take about 50 s for the capacitor to fully charge to 6 (or 9) volts.

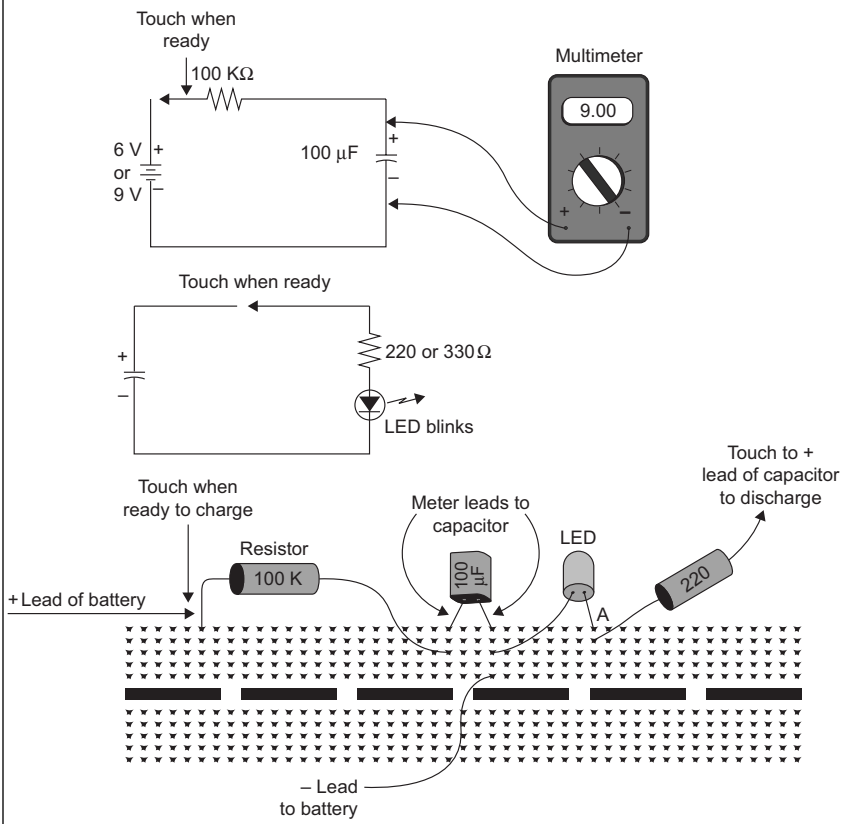


FIGURE 3.25 Circuits for charging and discharging capacitor and respective wiring.

Project 3.3—cont'd

Now disconnect the battery's positive lead. The capacitor retains the charge, as you should see on the meter. It will probably begin to drop slowly as it discharges into the meter.

Now use the capacitor as a voltage source. Connect the capacitor to the resistor and LED you used earlier as shown in Fig. 3.25. The capacitor will discharge quickly, and you should only see the LED blink briefly. To see it again, recharge the capacitor and repeat.

Project 3.4

Transistor Switch

A transistor makes a good switch, especially a MOSFET. And it is easy to use. This project demonstrates how the MOSFET can be used to turn the LED off and on.

Acquire a MOSFET, such as the IRF510, or an equivalent such as the 2N7000, etc. Then build the circuit shown in Fig. 3.26. Be sure to follow the guidelines for wiring the transistor. Use the LED and 220 (or 330)-Ω resistor that you used before.

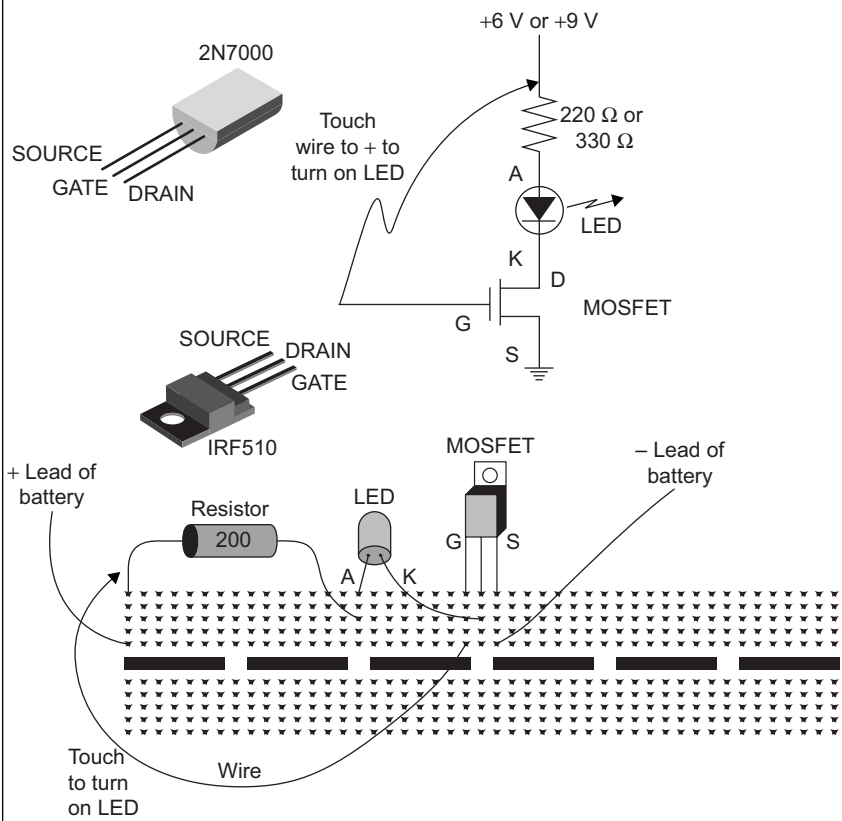


FIGURE 3.26 Circuit that turns an LED off and on with MOSFET and wiring.

Now, connect the battery. Touch the wire from the gate on the MOSFET to the +6 V or +9 V connection like on the resistor lead. This will turn the transistor on, and it will act as a switch to turn on the LED. Disconnect the gate from +6 V and the transistor switch goes off, turning off the LED.

Project 3.5

Measuring Resistance and Continuity

In some instances, you may need to measure a resistance. Your multimeter can do this. Here is a short project to give you some practice in measuring a resistor value. In addition, you will see how to use your multimeter to check for continuity, that is, to verify that there is a direct connection between two different points.

Get some of the resistors you used in the previous projects and check their color code. For example, one resistor may have the color code yellow–purple–red–gold. The color code says that this is a 4700-Ω 5% resistor. The 5% means that the actual value of the resistor will be between +5% and −5% of the color-coded value. 5% of 4700 is 235 Ω. So the resistor value will be between 4700 − 235 = 4465 and 4700 + 235 = 4935 Ω.

Now, choose a resistor and calculate the possible range. Then, use your multimeter to measure the actual value. Set the multimeter to the resistance (R) range. Try the different ranges to get the right reading. The resistor value should be within the range. You may want to repeat this process with another resistor to be sure you know how to do it.

Now check the continuity of something. This is the process of measuring the resistance between two points that should be connected together with a wire, connector, or other conductor. The resistance should be zero or very low. A good test is to measure the resistance of piece of wire. Wire does have resistance but it is very low and your meter may not record it.

If you have a roll of #22 hookup wire, measure its resistance. Set the multimeter to its lowest resistance range. The meter digital readout should initially be 1 meaning infinite resistance or an open circuit. Now touch the meter probes to the two ends of the wire. You should read 0 Ω or close to it. This means that the wire has continuity.

Note: Just remember that when you are measuring resistance or checking for continuity, there should be no current flowing or voltage applied. Remove the resistor completely from any circuit and disconnect any wire or cable from power before you use a multimeter on it. Otherwise, you will damage your meter.

Chapter 4

Electronic Circuits: Linear/Analog

The Building Blocks of Electronic Equipment

In this Chapter:

- Linear circuits defined.
- Types of linear circuits.
- Operation of the most common linear circuits such as amplifiers and power supplies.

INTRODUCTION

The basic building blocks of electronic equipment are individual circuits made up of transistors, resistors, capacitors, and sometimes transformers, inductors, or other components. It used to be that circuits were made up of individual discrete components that were wired together on a printed circuit board (PCB). But today, most electronic circuits are in integrated circuit (IC) form, or more likely multiple circuits are already combined on a single silicon chip to create a larger circuit, subsystem, or system on a chip.

While most circuits are ICs there are still some cases where discrete components are necessary or desirable. The most common examples are high voltage or high power circuits that would burn up a tiny silicon chip. Discrete components have not gone away entirely, and you will find some of them external to an IC such as larger capacitors or inductors that just cannot be easily integrated onto a chip or transistors that can handle higher voltage or power. As mentioned before, we are not going to talk about the makeup or operation of individual circuits. Instead, this book treats circuits as just building blocks with an input and an output that process the input in some way to create a new, different output.

LINEAR CIRCUITS

There are two basic types of circuits, linear and digital. Digital circuits are covered in the next chapter. Linear circuits are those circuits that process analog

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00004-7
Copyright © 2018 Elsevier Inc. All rights reserved.

signals. Recall that analog signals are those that vary smoothly and continuously over time in contrast to pulse and digital signals that are voltages that switch off and on very fast. Analog signals are like sine waves, voice signals, video signals, radio waves, and voltages from sensors like a temperature transducer. DC, either a constant value of voltage or one that is varying, is also an analog signal.

A linear circuit is one whose output is proportional to its input. See Fig. 4.1. Its so-called response is a straight line or what a mathematician would call a linear function. The best example of this is the amplifier where its output is proportional to its input so that it accurately reproduces the input faithfully but at a higher voltage or power level. In the figure, with 0.4-V input you get 4-V output. That means the amplifier has a gain of 10. Linear circuits do not distort the signal. This chapter covers linear circuits with most of the emphasis on amplifiers since that is the largest category of linear circuits. And as it turns out, most other types of linear circuits are just amplifiers connected in different ways to give different processing results.

Amplifiers

The basic block diagram symbol for an amplifier is a triangle. See Fig. 4.2. It has an input and an output. Amplifiers also have one or more DC inputs as well. This DC from a battery or other power supply is what powers the circuit, and it is this DC that is ultimately converted into the new, larger output signal. In most cases the DC inputs are not shown in a block diagram. The amplifier processes the input to create an output of the same shape but at a larger amplitude.

The primary characteristic of any amplifier is its *gain*. The gain (usually represented by A) is simply a number equal to the ratio of the output to the input.

$$A = \frac{\text{Output}}{\text{Input}}$$

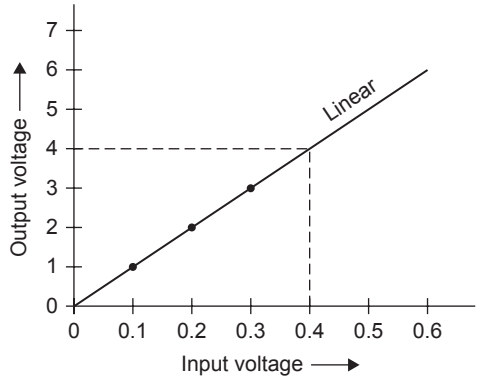


FIGURE 4.1 Linear circuit has a straight-line response. As input varies, output varies by factor of 10 larger, producing straight-line output.

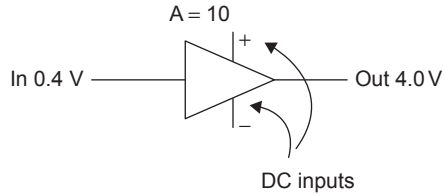


FIGURE 4.2 Block symbol for amplifier. Gain, A, is often given. DC power inputs are not usually shown.

If the output is 4 V and the input is 0.4 V, the gain is simply:

$$A = \frac{4}{0.4} = 10$$

The amplifier multiplies the input by 10 to get the output.

$$\text{Output} = 10 \times \text{Input}$$

Classifying Amplifiers

The amplifier is the most common linear circuit. There are so many different types of amplifiers that we divide them up into different types to distinguish one from another. And there are multiple ways of doing this. Here are the most common.

Small Signal Versus Large Signal

Small signal amplifiers are those that, as the name implies, only amplify small signals that are those roughly below about 1 V. Small signal amplifiers amplify millivolt, microvolt, or nanovolt signals. Large signal amplifiers amplify larger signals and typically amplify the power of a signal rather than the voltage. These are called power amplifiers (PAs).

Frequency Classification

Amplifiers are also categorized by the frequency of the signals they amplify. Some examples are DC amplifiers, audio frequency amplifiers, intermediate frequency (IF) amplifiers, video amplifiers, radio frequency (RF) amplifiers, and microwave amplifiers.

Configuration Classification

The two main configurations are single ended and differential. A single-ended amplifier is one in which the input and output are referenced to a common ground. These amplifiers have two inputs, one is the signal and the other is ground. See Fig. 4.3A. Normally only the input is shown as the ground is just assumed to be there.

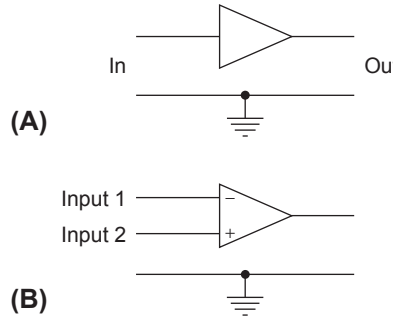


FIGURE 4.3 Single-ended (A) and differential input (B) amplifiers. Inputs and outputs are referenced to ground.

A differential amplifier has two inputs as Fig. 4.3B shows. These are usually called the inverting (2) and the noninverting (1) inputs. Both inputs are referenced to ground. The amplifier is called a differential amplifier because it actually takes the mathematical difference between the two inputs and amplifies the result. One input is subtracted from another, then the difference is amplified by the gain A. The formula for this operation is:

$$\text{Output} = (\text{Input } 2 - \text{Input } 1) \times \text{A}$$

Differential amplifiers have one neat feature in that any signal common to both inputs like noise is automatically canceled out. This feature is widely taken advantage of in very small signal amplifiers used in memory chips and high gain amplifiers that amplify small signals from sensors. Noise that is picked up simultaneously on both inputs simply subtracts itself out without bothering the desired small difference signal.

Classification by Class of Operation

One way to categorize amplifiers is to designate the conduction of the transistors in the amplifiers. The primary classes are A, B, AB, C, D, E, and F. There are a few others but these are the most common. Class A amplifiers conduct continuously. We say that the amplification occurs over the full 360 degrees of a sine wave cycle. See Fig. 4.4. Note: The "t" on the waveforms means time as the voltage is varying over time.

Class B amplifier transistors only conduct for half a cycle or 180 degrees of a sine wave. See Fig. 4.5. Such an amplifier seems useless since it distorts the signal. But if you combine two transistors, one to amplify positive cycles and the other to amplify negative cycles, then combine the two, the complete wave is amplified. Such an amplifier is called a push–pull amplifier. The benefit of this arrangement is that the circuit is more efficient.

Class AB amplifiers are a variation of the class B. Class B amplifiers do add a little distortion to the signal around the point where the sine wave crosses

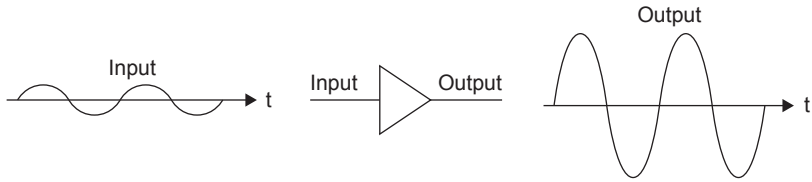


FIGURE 4.4 Class A amplifier conducts continuously.

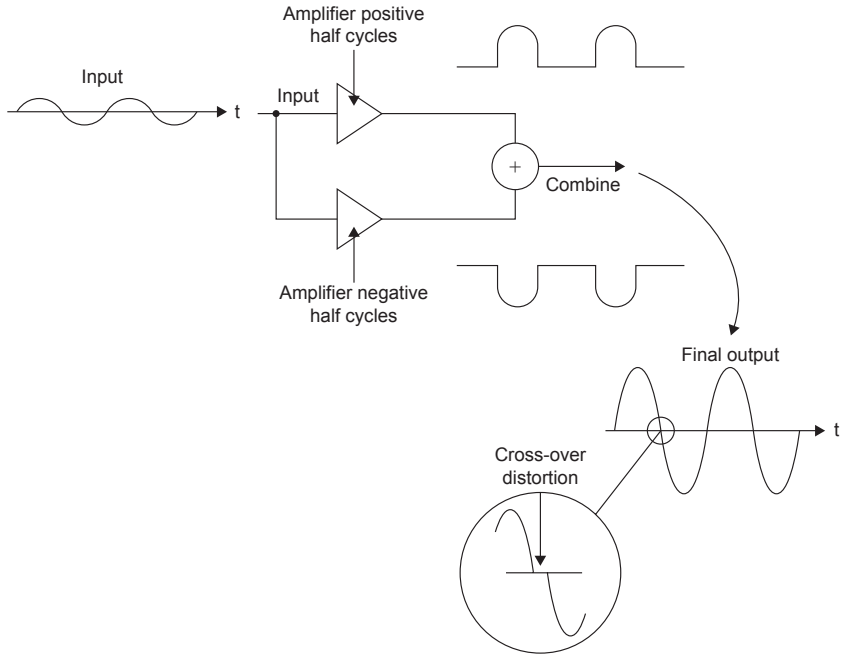


FIGURE 4.5 Class B amplifier conducts half the time, making it more efficient.

zero. This is caused by the transistors not turning on and off precisely at the zero point. This glitch shown in Fig. 4.5 is called crossover distortion. To get rid of that, class AB amplifiers allow some small current to flow continuously. The result is less distortion but a little less efficiency.

Class C amplifiers are for RF signals and are usually PAs. They only allow the transistor to conduct for less than 180 degrees of a sine wave input, usually 90–150 degrees. It produces massive distortion. However, the amplifier output is made up of an inductor and capacitor (LC) tuned circuit that oscillates at the operating frequency and removes the distortion. These amplifiers are very efficient.

In a class C amplifier the MOSFET acts like a switch that is turned off and on by the input signal, usually a sine wave. See Fig. 4.6. When the MOSFET is on, the capacitor charges up to the DC supply voltage and current flows in the

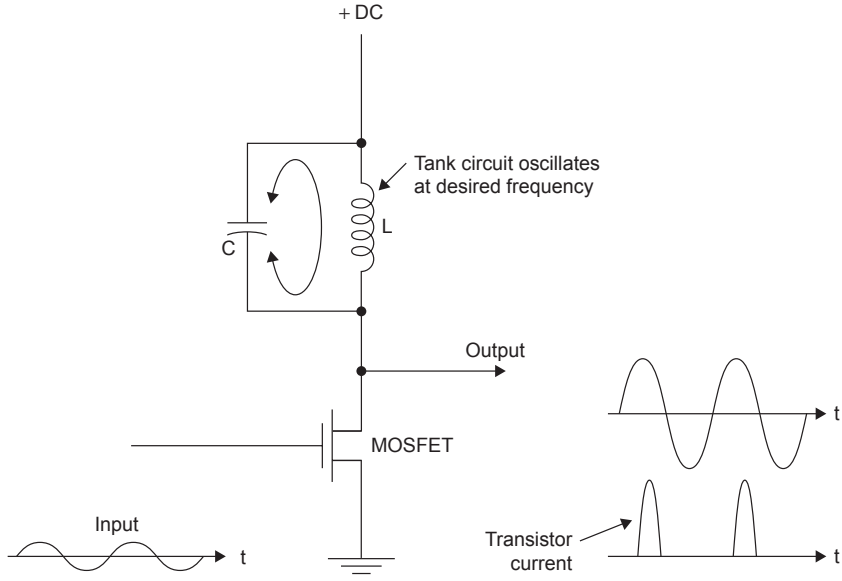


FIGURE 4.6 Class C amplifier only conducts for part of a half cycle, but the current pulse stimulates resonant tank circuit that oscillates at desired frequency.

inductor creating a surrounding magnetic field. When the transistor turns off, the inductor and capacitor begin to exchange energy and set up an oscillation at the resonant frequency of the LC circuit. This is called a tank circuit. The result is that the energy stored in the tank circuit produces the amplified sine wave output.

Another way of looking at this is that the transistor switch distorts the input creating a pulse waveform that contains lots of harmonics. The tank circuit acts like a selective band-pass filter that lets the fundamental sine wave pass while the harmonics are filtered out.

Don't forget the Fourier theory and harmonics. Remember that a harmonic is an integer multiple of a fundamental sine wave. If the fundamental sine wave is 20 MHz, the second harmonic is 40 MHz, the third harmonic is 60 MHz, the fourth harmonic is 80 MHz, and so on. Any nonsine wave signal, such as a half sine wave, square wave, or pulse is said to be made up of the fundamental sine wave added to multiple harmonics. A distorted sine wave has the fundamental sine wave in it but also harmonics. This concept is called the Fourier theory after the French mathematician.

Class D amplifiers are a special class called a switching amplifier. It is made up of transistor switches rather than a real linear amplifier. This amplifier chops the input analog signal into high-frequency pulses with a varying width. See Fig. 4.7. This process is called pulse width modulation (PWM). The sine wave audio signal to be amplified is sent to one input of a special amplifier called a comparator

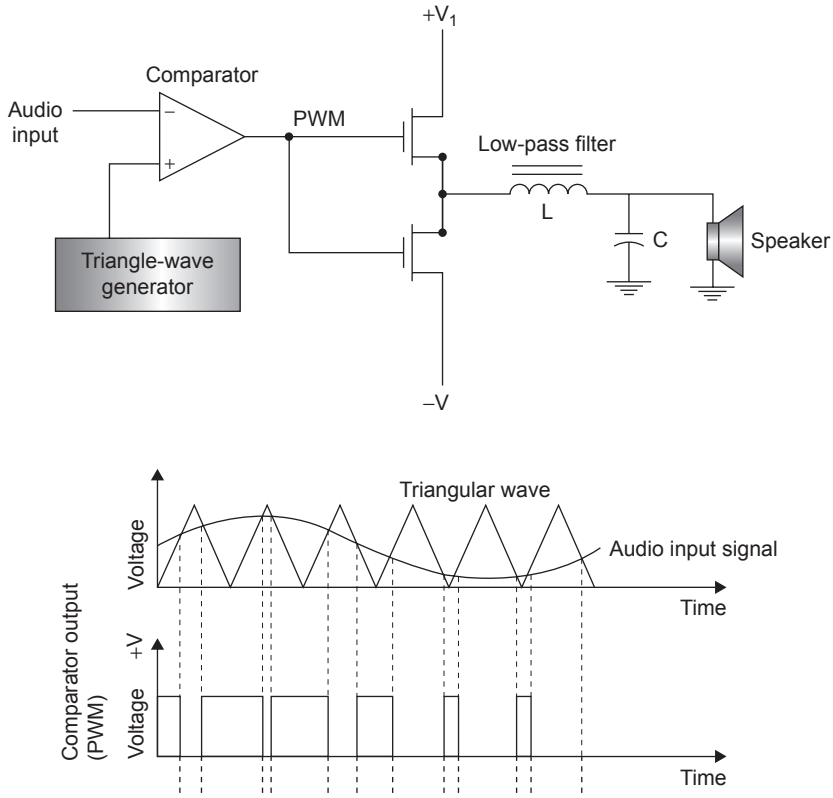


FIGURE 4.7 Class D amplifier uses pulse width modulation (PWM) at higher frequency to switch higher voltages for greater output. Class D amplifiers are more efficient than any other type, and thus do not produce as much heat.

along with a higher-frequency triangle wave. The comparator output switches when the triangle wave and sine wave values are equal. The resulting PWM signal is then fed to MOSFET switches to make the signal bigger. The higher amplitude output it then filtered back into an analog signal by a low-pass filter (LPF) made up of a capacitor and inductor. Most class D amplifiers are audio PAs whose load is a speaker or headphone. For low power less than a few watts, all the circuitry is in a single IC. For higher power, the MOSFETs are larger external devices.

The big benefit of switching amplifiers is that for a given output power they are very efficient. Whereas a class AB amplifier may only be 20%–30% efficient, the class D is over 90% efficient. This means that the amplifier can be smaller and use less power and dissipates less heat. Class D amplifiers are great for portable battery-operated devices such as MP3 players and cell phones.

Classes E and F are special switching amplifier variations used at RF frequencies only. Like the class C amplifier, they use LC circuits to filter out the harmonics they produce. They are very efficient.

Operational Amplifiers

There are many special types of amplifiers. The most widely used is the operational amplifier, or op amp. This is a versatile high-gain DC differential amplifier that can be configured with external resistors, capacitors, diodes, etc., to perform a wide variety of amplification functions. The op amp may be the most widely used type of amplifier because of its versatility.

Fig. 4.8 shows the most common op amp configurations. In most cases, the resistors are external to the IC amplifier. Note that the gain is determined by the values of the external resistors. Note formulas for gain (A).

A variation of the op amp is the instrumentation amplifier. See Fig. 4.9. It is a combination of multiple op amps that make it very useful in industrial

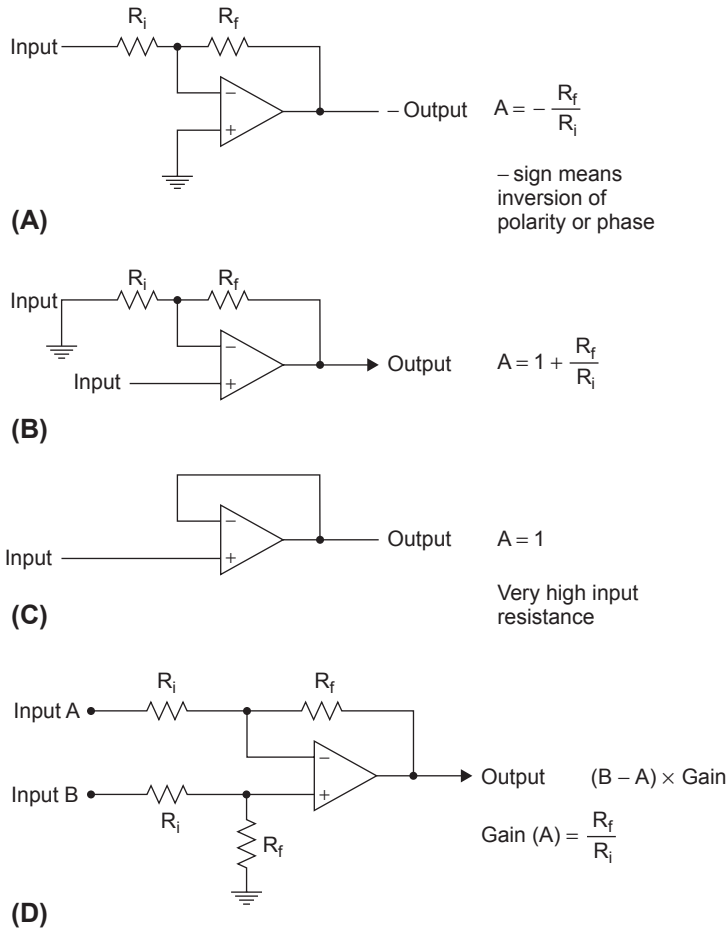


FIGURE 4.8 Most commonly used operational amplifier circuit configurations. (A) Inverting amplifier, (B) noninverting amplifier, (C) follower, and (D) differential amplifier.

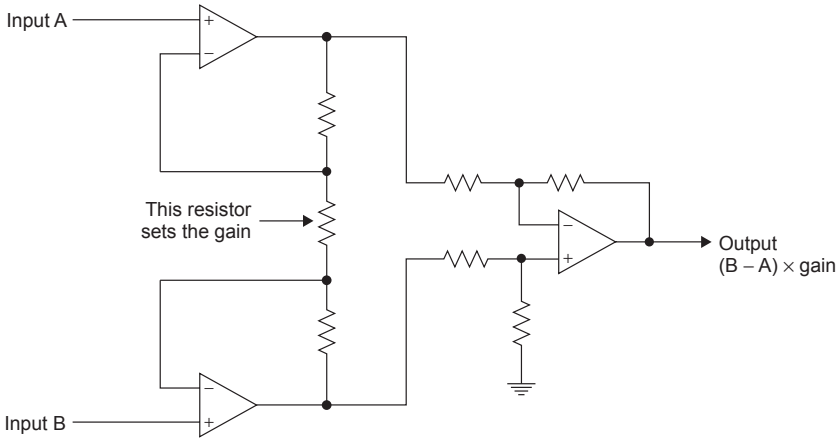


FIGURE 4.9 Instrumentation amplifier widely used to amplify small sensor signals in industrial applications.

applications such as amplifying small signals from sensors. Again the gain is determined by the resistor values. You can make this amplifier from individual op amps but usually you just buy it as a single IC. The external resistor sets the gain.

A variable or programmable gain amplifier is one whose gain can be controlled from an external DC input.

Amplifier Specifications

While you really do not need to know much about what the circuitry in an amplifier IC is, you do need to understand the specifications. Here are the most common specifications to look for.

As mentioned before, gain is the primary amplifier characteristic. It is usually a voltage or power ratio, depending on the type of amplifier.

$$\text{Voltage gain is output voltage over input voltage}: A_v = \frac{V_o}{V_i}$$

$$\text{Power gain is output power over input power}: A_p = \frac{P_o}{P_i}$$

Many amplifiers have their gain expressed in decibels (dBs). A dB is a gain measurement based on a logarithmic scale rather than a linear scale. This has the advantage of being able to express large and small gains in smaller numbers. And gains of multiple stages can be added rather than multiplied. To calculate dB gains you used these formulas:

$$\text{Voltage gain}: \text{dB} = 20 \log (A_v)$$

$$\text{Power gain}: \text{dB} = 10 \log (A_p)$$

In these formulas, log means the common (base 10) logarithm of the voltage or power gain. The logarithm (log) is easy to find using a scientific calculator.

For example, a voltage gain of 50 expressed in dB is:

$$\text{dB} = 20 \log 50 = 20\,(1.7) = 34 \text{ dB}$$

A power gain 300 expressed in dB is:

$$\text{dB} = 10 \log 300 = 10\,(2.5) = 25 \text{ dB}$$

Input Impedance

Input impedance is the load seen by the signal source to the amplifier. It is usually resistive but typically also has some capacitance across it. Fig. 4.10A shows an equivalent circuit of an amplifier. Note the input resistance. That is the input impedance. It may be as high as several megohms or could be as low as, say, 50 Ω. Usually the higher the better for voltage amplifiers but not for PAs.

Impedance

The term *impedance* means opposition to current flow. It is actually the combined opposition offered by resistance plus any capacitive or inductive reactance. If there is no reactance, the impedance is just the resistance so the two terms can be used interchangeably. Impedance is represented by the letter Z.

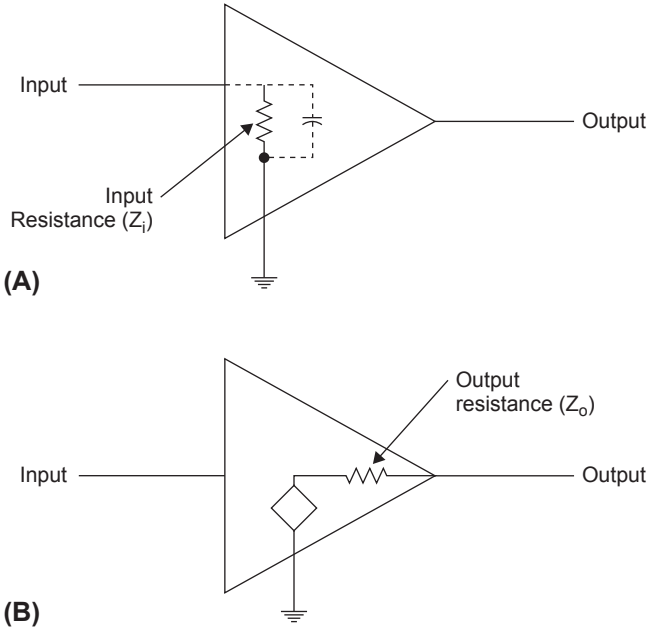


FIGURE 4.10 Amplifier input impedance (A) and output impedance (B).

Output Impedance

Amplifiers act as signal generating sources because they essentially just create a new higher voltage or higher power signal with the same shape as the input. They appear as a signal generator to the next circuit or load. Fig. 4.10B shows the amplifier as a generator shaped as a diamond. It has an internal impedance or series resistance called the output impedance. It is not a real resistor but it is there and it appears in series with whatever load is connected, which may be another amplifier or something else.

Fig. 4.11 shows the amplifier connected to another amplifier. Note that the output impedance for amplifier A_2 and the load form a voltage divider so some of the amplification is lost to the voltage divider effect. The input impedance of A_2 is the load for the output impedance of A_1.

Cascading Amplifiers

If an amplifier does not have enough gain, then multiple amplifiers can be cascaded one after the other to give the needed gain. One amplifier amplifies the output of the next and so on. See Fig. 4.12. To calculate the overall gain of an amplifier you just multiply the gains as shown in the figure. This procedure assumes that one amplifier does not load the next. That is, the output impedance

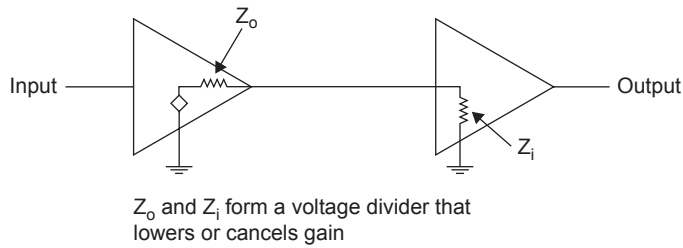
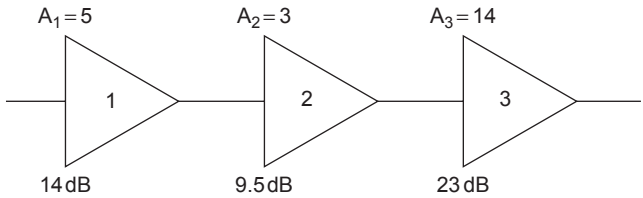


FIGURE 4.11 When one amplifier feeds another, input and output impedances form a voltage divider that attenuates the signal and offsets some of the gain.



$A_T = A_1 \times A_2 \times A_3$
$A_T = 5 \times 3 \times 14 = 210$
$A_T = 14 + 9.5 + 23 = 46.5\,dB$
$210 = 46.5\,dB$

FIGURE 4.12 Cascading amplifier provides more gain. Total gain is product of individual gains or sum of decibel (dB) gains.

of each amplifier is assumed to be zero and the input impedance of the next amplifier is assumed to be infinite. That way, there is no voltage divider effect that lowers the gain.

If the amplifier gains are given in dB, you just add the dB figures to get the total gain.

Efficiency

Efficiency is the ratio of the output power to the input power expressed as a percentage.

$$\% \text{ Eff} = \frac{P_o}{P_i} \times 100$$

An amplifier takes the DC supply voltage and converts it into the AC output. The efficiency expresses how well the amplifier does this. Any lost power usually gets converted to heat which is not good. Nevertheless, some heat will always be generated just because electronic circuits are not perfect. High efficiency is a good thing of course, but often efficiency is traded off for better linearity, fidelity, and lower distortion of the signal.

Class A amplifiers have the poorest efficiency commonly in the 10%–30% range. Classes B and AB are more efficient in the range of 50%–70%. Class C amplifiers have an efficiency of 70%–85%. Class D amplifiers are the best with efficiencies in the 80%–95% range.

Frequency Response

This is a measure of the range of frequencies that amplifiers cover. DC amplifiers may only cover DC up to about a few hundred Hertz. Audio amplifiers may cover voice frequencies from 300 to 3000 Hz or stereo amplifiers that cover 20 Hz–20 kHz. IF amplifiers may only cover a specific band, say, 455 kHz, 9 MHz, 45 MHz, 70 MHz, or some other popular IF value. Op amps amplify signals from DC up to some very high frequency as high as several hundred MHz in some cases.

RF amplifiers cover high radio frequencies from a few MHz up to microwaves from 1 to 100 GHz. Their frequency and range of coverage is usually set by a filter or LC tuned circuit.

Fig. 4.13A shows the response curve for an op amp with an output down to DC and up to the cutoff frequency (f_{co}) or 5 MHz. Fig. 4.13B is the response curve of a stereo amplifier with a range of 20 Hz–20 kHz.

Output Capability

This specification indicates the range of output signals the amplifier is capable of. It is usually stated as a maximum voltage swing or as a maximum amount of output power. In both cases, the maximum output is usually given for a given value of load resistance. For example, an op amp may be capable of producing

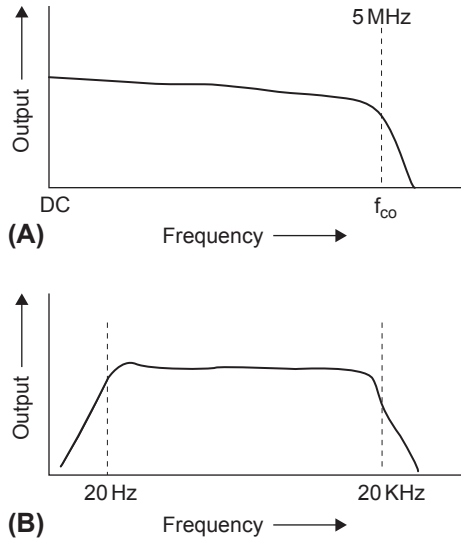


FIGURE 4.13 Frequency-response curves show output versus input frequency. Curve in (A) is response of operational amplifier that extends from DC to 5-MHz cutoff frequency. Curve in (B) is response of common stereo audio amplifier.

an output of ±12 V across a 2-k load. A PA may produce a maximum output of 10 W across an 8-Ω speaker load or, say, 50 W across a 50-Ω antenna load.

Filters

A filter is a frequency sensitive circuit that is designed to pass some frequencies, but reject others. There are various ways of making filter circuits that will accept some frequencies, but greatly attenuate others. There are literally thousands of applications for such circuits. But the main use of filters is to retain a desired signal, but eliminate interference and noise.

There are four basic types of filters: LPF, high-pass filter (HPF), band-pass filter (BPF), and band-reject filter. The names, of course, tell their function.

A LPF is a circuit that passes all frequencies between DC and some upper cutoff frequency (f_{co}). All frequencies above the cutoff frequency are rejected. Fig. 4.14A shows the response curve of an LPF. This is a plot of the filter output amplitude versus frequency. Note the gradual slope as signals above the cutoff frequency (f_c) are reduced in amplitude. The block symbol is how LPF is represented in some diagrams.

A high-pass filter passes frequencies above the cutoff and greatly attenuates those below the cutoff. Fig. 4.14B shows the ideal response curve of an HPF. Note the HPF symbol.

BPF pass a certain range of frequencies, but reject all those above and below that range. Fig. 4.14C shows the practical response curve of a BPF. Note that

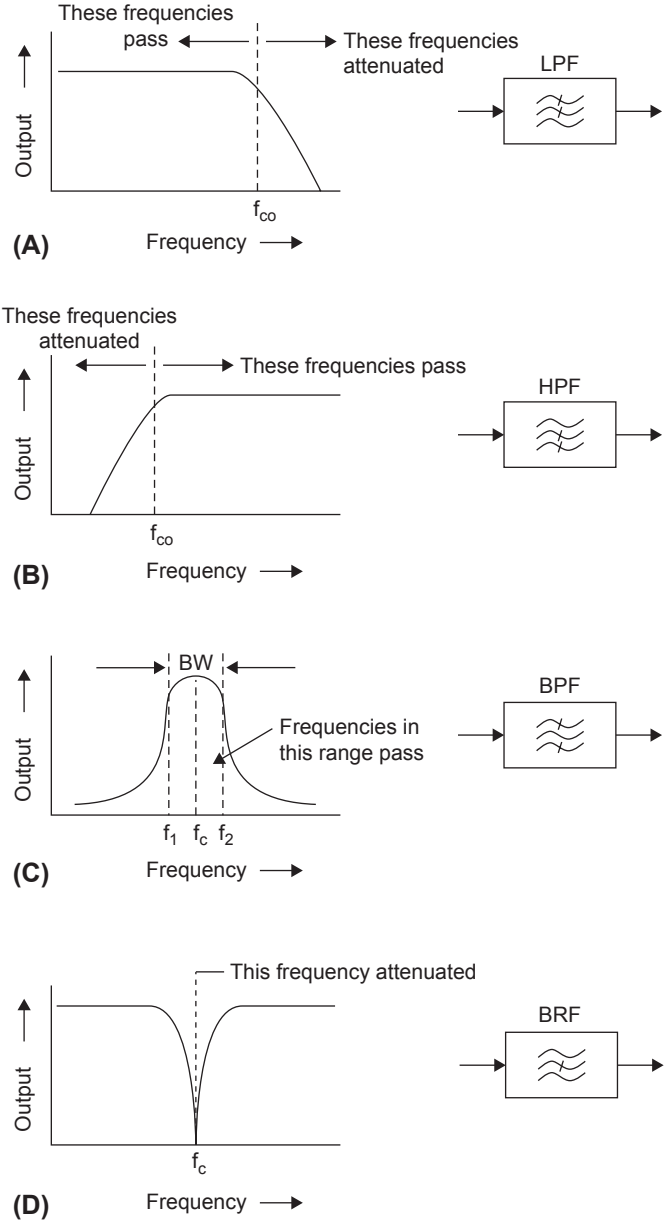


FIGURE 4.14 Four common filter types and their response curves and symbols. (A) Low-pass, (B) high-pass, (C) band-pass, and (D) band-reject or notch.

there are two cutoff frequencies, one above and one below the center frequency f_c. The difference between the upper and lower cutoffs is called the filter bandwidth (BW):

$$BW = f_2 - f_1$$

This is the range of frequencies passed. Again note the schematic symbol for a BPF.

Fig. 4.14D illustrates the curve for a band-reject or notch filter. It is used to eliminate one single frequency and those close around it.

Note in the block symbols in Fig. 4.14 that each has three waves representing high, middle, and low frequencies. The wave with the slash through it means that these frequencies are cut out or greatly attenuated.

Filters can be implemented in many ways. Resistor and capacitor (RC) filters are common as are LC filters. You can make filters with op amps called active filters. Other filters are made with mechanical vibrating elements, a ceramic or quartz crystal, or a special surface acoustic wave filter. Many filters today are made with digital signal processing. These will be discussed in Chapter 6.

Oscillators

An oscillator is a circuit that generates a signal. It is usually a sine wave or a rectangular wave. The electronic symbols used to represent an oscillator are given in Fig. 4.15.

The main specification of an oscillator is its output frequency. Most oscillators have a fixed frequency but there are oscillators whose frequency can be varied. A tunable frequency oscillator is called a variable frequency oscillator.

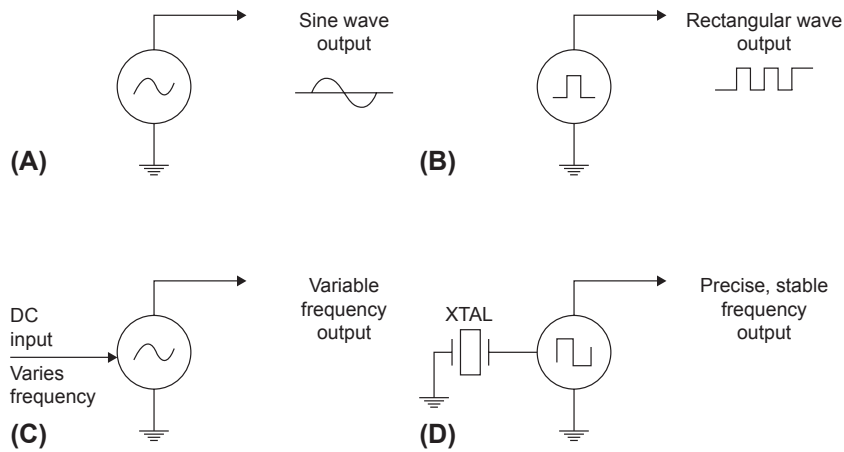


FIGURE 4.15 Types of oscillators and their symbols. (A) Sine wave, (B) rectangular pulse, (C) voltage-controlled oscillator, and (D) crystal clock oscillator.

You can often tune it by turning a knob that varies a capacitor or inductor to change the frequency. Some oscillators are tuned by an external voltage. These are called voltage-controlled oscillators (VCOs). By varying the value of a DC input voltage, the frequency is changed.

The frequency of an oscillator is set by some frequency determining element or circuit. That circuit may be made up of RC, LC, or a crystal. A crystal is a thin piece of quartz that can be made to vibrate at a very precise frequency. It maintains its frequency very closely unlike RC or LC networks that can drift with temperature or change from vibration or other conditions. Crystals come in a small metal package and are used to set the frequency in most oscillators today.

A special type of oscillator is called a clock oscillator. It is used as an accurate time and frequency source. The frequency determining element is usually a quartz crystal that vibrates at a precise frequency and is very stable. The clock signal is used to operate all the circuits in synchronism. An example is the clock oscillator in a PC that sets the speed of calculations. Sometimes you will see a quartz crystal (XTAL) symbol drawn with the oscillator symbol to illustrate this. See Fig. 4.14D.

Mixers

A mixer is a circuit that takes two input signals and mixes them in a special way to produce new output signals. There are two types of mixers, linear and nonlinear.

A linear mixer is one that takes the input signals and just adds them together. You can do this with some resistors as shown in Fig. 4.16A. The sum of both input signals appears across the output resistor.

You can also make a linear mixer with an op amp as shown in Fig. 4.16B. This op amp circuit is called a summer. Setting the resistor values allows you to mix and add gain at the same time. A good example of a linear mixer is those used by musicians so they can mix the outputs from microphones and musical instruments so they can all be amplified as one by the PAs that drive the speakers. Note the variable resistors called pots that are used as amplitude or volume controls.

A nonlinear mixer takes two input signals and effectively multiplies them together. The result is that the mixer produces four output signals. Fig. 4.17 shows the symbol for a mixer. The inputs are frequencies 1 and 2, or f_1 and f_2. The mixer outputs are f_1, f_2, and (f_1+f_2) or the sum, and (f_1-f_2) or the difference. The sum and difference frequencies are the ones of most interest. Usually a filter is used at the output of the mixer to select the desired frequency and eliminate the others. If the lower difference frequency is selected, the mixer is often called a down converter. If the sum frequency is selected, the mixer is called an up converter. The mixer is a way to translate a frequency to another

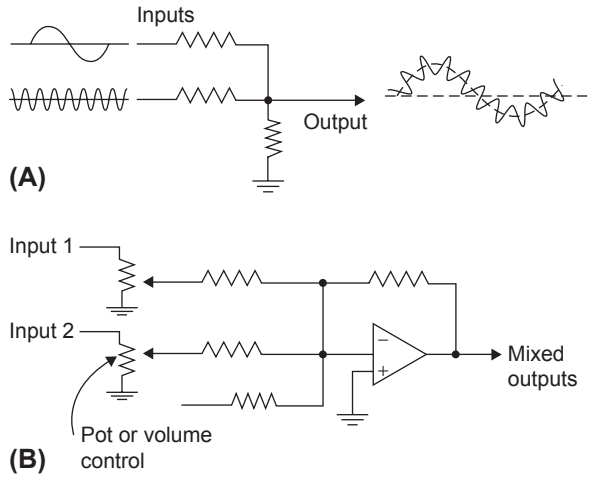


FIGURE 4.16 Linear mixing with resistors (A) or an operational amplifier summer (B).

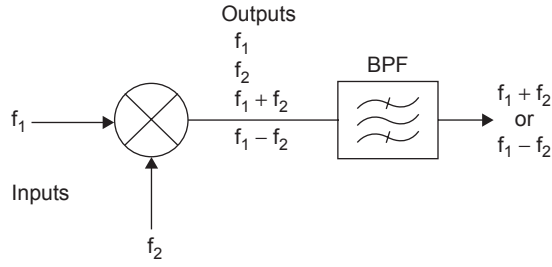


FIGURE 4.17 Nonlinear mixer used to generate higher and low frequencies.

higher or lower frequency that is better for processing. Any signal amplitude or frequency variations on the inputs are accurately carried through to the new output frequency.

Phase Detector

A phase detector is a mixer-like circuit that puts out a signal that is proportional to the phase difference between two input signals of the same frequency. See Fig. 4.18. A phase shift is a time difference between two signals of the same frequency. We sometimes need to know how much phase shift is present. The phase detector produces a series of output pulses whose width is proportional to the phase difference. Passing the pulses through a LPF smoothes them into a proportional DC voltage.

Filtering Pulses Into DC

A common occurrence in electronic circuits is the filtering of pulses into a DC voltage. You saw this back in Fig. 3.15 where positive pulses from a sine wave rectifier are smoothed into a near constant DC voltage. It is the capacitor that charges up and stores the pulse voltage. Then between pulses the capacitor discharges into the load maintaining a near constant DC voltage. The LPF usually includes a capacitor so performs the same function in the phase detector of Fig. 4.18. The output is a proportional average DC output.

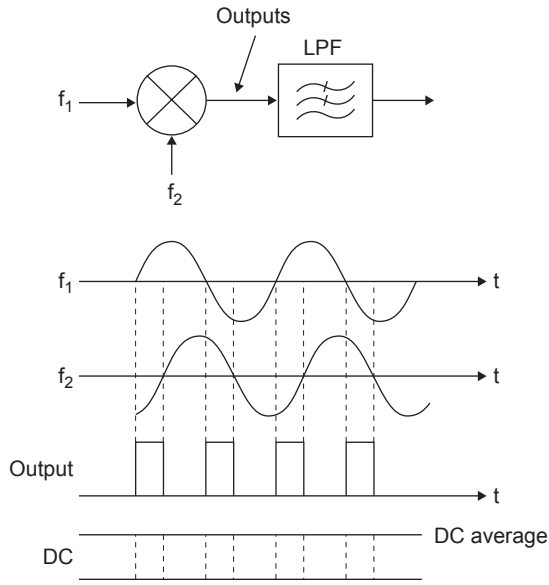


FIGURE 4.18 Phase detector converts phase shift into proportional DC average.

Phase-Locked Loops

The phase-locked loop (PLL) is a frequency- and phase-sensitive feedback control circuit. It consists of three major parts: a mixer or phase detector, a LPF, and a VCO, as shown in Fig. 4.19. The signal from the VCO is compared to the input signal. If there is a frequency (or phase) difference between the two, an error signal is generated. This error signal is filtered by the LPF into a varying DC level and is used to control the VCO frequency. This is the feedback signal.

If the VCO frequency, f_o, differs from the input reference signal frequency, the phase detector sees this as a phase shift. This causes the phase detector to produce an error signal. This error signal is filtered into a varying DC signal that is used to control the VCO.

The VCO can be either a sine wave oscillator or a rectangular wave oscillator depending upon the desired waveshape of the output. In either case, the VCO

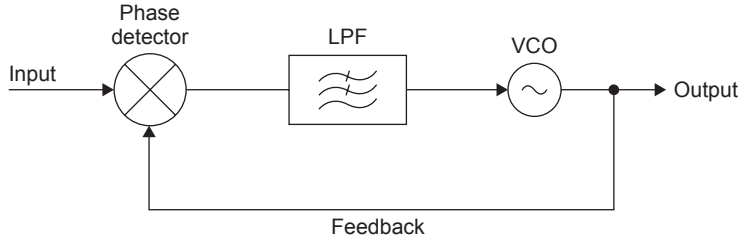


FIGURE 4.19 Phase-locked loop.

output frequency is made directly proportional to the DC control voltage. There is a linear voltage-to-frequency relationship in the VCO. This means that changing the control voltage produces a proportional change in output frequency. If the voltage goes up, so does the frequency.

Now if an input reference signal whose frequency is near that of the VCO is applied to the PLL, the phase detector will produce an output voltage proportional to the frequency difference. This signal is filtered and the resulting DC control voltage is applied to the VCO. The control voltage is such that it forces the VCO frequency to move in a direction that reduces the error signal. This means that the VCO frequency will change until it is equal to the input reference signal frequency. When this happens, the two signals are synchronized or "locked." The phase difference causes the phase detector to produce the DC voltage at the VCO input to keep the PLL locked to the input signal.

If the input reference signal changes, then the phase detector will recognize a frequency (or phase) difference between the input and the VCO output. As a result, the LPF will produce a different DC control signal that will force the VCO to change such that it is equal to the new input frequency. As you can see then, the PLL will "track" an input signal frequency as it changes.

The range of frequencies over which the PLL will track an input signal and remain locked is known as the lock range. This is a range of frequencies above and below the VCO free running frequency. The PLL can track and "lock" to any input frequency in this range. If an input signal out of the lock range is applied, the PLL will not synchronize.

If the input signal is initially outside of the lock range, the PLL will not lock. But, the PLL will jump into a locked condition as soon as the input frequency gets close to the VCO frequency. In other words, the PLL will "capture" the incoming signal if it is close enough to the VCO frequency. Once the input signal is captured, the PLL is locked and will track further changes in the input signal frequency.

The range of frequencies over which a PLL can capture a signal is known as the capture range. Like the lock range, it too is centered on the free running frequency. But the capture range is narrower than the lock range. The PLL acts as a frequency sensitive circuit over a narrow range of frequencies.

Since the PLL will only capture and lock on to input signals within a certain narrow band, the PLL acts like a band-pass filter. For that reason, the PLL is an excellent signal conditioner. You can take a noisy input signal or one with undesirable interference on it and filter it with a PLL. The PLL will lock on to only the desired frequency component of the input. The VCO reproduces the input signal at the same frequency but with the noise and interference removed. The PLL not only cleans up a signal but also can track it if its frequency changes.

The PLL is widely used for a variety of purposes. It is used to recover the clock signal in some wireless applications. It is used to recover the original signal in frequency modulation radio. It is used to multiply a frequency by a fixed factor. It can be used for motor speed control. Almost all electronic products of some kind contain a PLL.

Frequency Synthesizers

One of the most popular uses of the PLL is in frequency synthesizers. A frequency synthesizer is a very stable signal source that can be varied over a specific range of frequencies in finite increments or steps. Frequency synthesizers are used as precision signal generators for test and measurement purposes and replace more conventional oscillator circuits as the primary signal sources in radio transmitters or receivers.

The big advantage of a PLL synthesizer is its ability to generate a wide range of frequencies with great accuracy and stability by using only a single stable signal source. For example, a PLL synthesizer with a single crystal controlled reference input can readily generate hundreds or even thousands of discrete frequencies that are as stable as the crystal reference. By using a synthesizer as the initial signal source in a transmitter, a wide range of channels can be obtained with a single crystal. When many channels must be used, a synthesizer greatly reduces the cost since crystals are expensive.

The synthesizer circuit in Fig. 4.20 shows that it is a PLL with a frequency divider connected between the VCO output and the phase detector. The frequency divider is a circuit that divides its input frequency by some whole number. For example, the output of a divider with a division factor of 12 and an input of 48 MHz is 48/12 = 4 MHz.

The frequency synthesizer PLL also uses a stable, crystal oscillator input to the phase detector. This is usually derived from a crystal oscillator. When the PLL is locked, the stability and accuracy of the VCO output will be the same as that of the reference input. The frequency divider is usually made so that its divide ratio can be changed by setting a switch or changing the control inputs. Changing the division ratio changes the output frequency at which the loop will lock.

The reason for this is that the two inputs to the phase detector must always be equal in frequency if a locked condition is to be achieved. The reference frequency is fixed so the only thing that can change is the VCO output if the divider

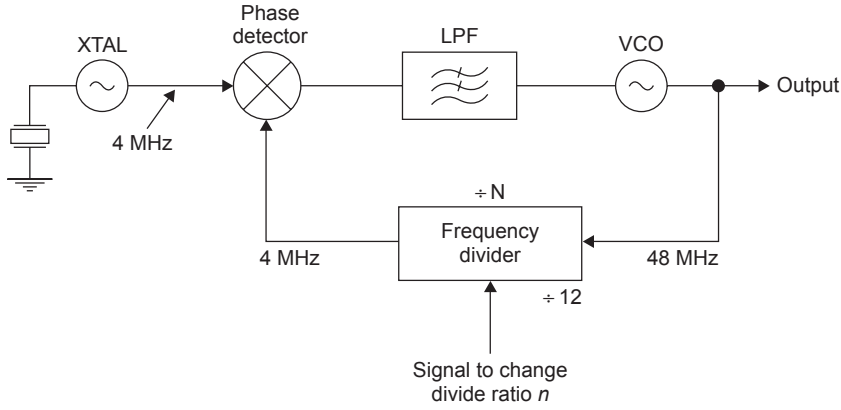


FIGURE 4.20 Frequency synthesizer using phase-locked loop. Changing the divider ratio changes the frequency. *LPF*, Low-pass filter; *VCO*, Voltage-controlled oscillator.

ratio is altered. If the loop is locked, the output of the divider will be 24 MHz no matter what the divide ratio is. Therefore, with an output of 4 MHz, a divide by six circuits must have a 24 MHz input. Since the VCO output is the divider input, the VCO and synthesizer output will be 24 MHz too.

As you can see, changing the divide ratio changes the output frequency. In this circuit, if the divide ratio is changed in integer values between 6 and 12, the output frequencies will be as shown in Table 4.1. With this setup, the output is switched in 4-MHz increments.

If the input reference is made 1 MHz, then when the divide ratio is changed, the output frequency will step in 1-MHz increments. By carefully selecting the reference frequency and the divide ratio, it is possible to synthesize practically any range of frequencies in many increments from subaudio to microwave.

Note one final fact about the PLL circuit in Fig. 4.20. If the reference is considered the input, and the VCO is considered the output, then the PLL is acting as a frequency multiplier. Here the output is 12 times the input. You will occasionally see the PLL used as a frequency multiplier in some applications.

The PLL synthesizer is a very versatile circuit. It is commonly available in IC form. PLL frequency synthesizers are used in TV channel selectors, stereo receivers, CB radios, cellular telephones, and other two-way radios. In such equipment the divider ratio is supplied by an input keyboard or a built-in microcomputer programmed to supply the desired divide factor for a selected output frequency.

A newer method of frequency synthesis is called direct digital synthesis (DDS). It uses digital circuits such as registers, adders, an accurate clock, a memory, a digital-to-analog converter to produce highly accurate sine waves and other waves whose frequency can be changed in small increments. The DDS is covered at the end of Chapter 5.

TABLE 4.1 Phase-Locked Loop Divide Ratio and Voltage-Controlled Oscillator (VCO) Output

Divide Ratio	VCO Output (MHz)
6	24
7	28
8	32
9	36
10	40
11	44
12	48

Power Supplies

A power supply is, as its name implies, a source of power to an electronic circuit. Most electronic circuits operate from DC as they process AC or DC signals. The most common power supply is the one that gets its input from the standard AC wall outlet that supplies 120 V at 60 Hz. This common voltage is then converted by the power supply into one or more DC voltages that go to operate the TV set, computer, or other equipment. This section discusses the main components and circuits of a power supply.

Batteries

One of the most widely used power supplies is a battery. A battery is a great source of DC by itself and no AC source is needed. Batteries were the very first form of voltage sources for electrical circuits, and they are still widely used today. What would we do without the batteries for our cell phones, iPods, cordless telephones, laptop computers, and remote controls? Just remember that a special form of power supply is the battery charger that normally uses AC to recharge lead–acid, nickel cadmium, nickel metal hydride, and lithium-ion batteries.

Standard Power Supply

A very common AC to DC power supply is shown in Fig. 4.21. It normally consists of a transformer that translates the 120-V AC line voltage into a higher or lower voltage as needed by its step up or step down characteristics. Today, since most equipment uses ICs, a lower AC voltage is needed. The lower AC voltage is then converted into a pulsating DC voltage by a rectifier. A rectifier is one or more diodes that act like polarity sensitive switches to change the positive and/or negative sine half cycles into pulses of DC. A filter is then used to smooth the pulses into a more constant DC voltage. The filter is usually a large capacitor

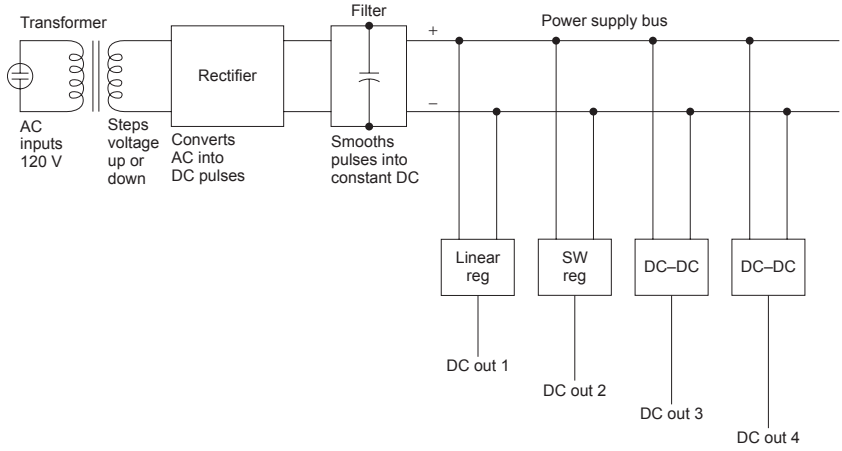


FIGURE 4.21 Typical power supply configuration using bus architecture, regulators, and DC–DC converters to get desired number of outputs. *reg*, Regulator.

that charges up to the peak of the DC pulses then only discharges very slowly into the load.

Regulators

A regulator is a circuit that maintains a fixed DC output voltage of a desired value. The DC produced by the power supply at the filter output will vary over a wide range as the AC input line voltage changes. Any changes in the load meaning variations in current taken from the supply will also cause the output voltage to vary. A regulator absorbs those variations and creates a constant DC output suitable for powering ICs and other electronic circuits. Common DC output voltages are 3.3, 5, 12, 15, and 24 V. Other typical DC supply voltages are 1.2, 1.8, 6, and 48 V.

There are two types of regulators, linear and switching. A linear regulator inserts a transistor in series between the power supply output and the load. If the load varies, circuitry in the regulator adjusts the conduction of the transistor so that a constant voltage is maintained. It is as if a resistor in series with the load forms an adjustable voltage divider. If the output voltage drops, the series transistor conducts more to keep the output voltage the same. If the output increases, the transistor conducts less to decrease the voltage and maintain the same value.

The other type of regulator is the switching regulator. It puts a transistor in series with the load as well but the internal circuitry turns the transistor off and on at a high rate of speed. By varying the duty cycle (ratio of on to time for one period) of the on–off pulses, the average DC output may be varied. Then if any output voltage changes are sensed, the duty cycle is adjusted to ensure that the average output stays the same.

Duty Cycle and Pulse Width Modulation

The duty cycle is the ratio of the pulse width to the period of a rectangular wave as shown in Fig. 4.22. The period is the reciprocal of the frequency of the signal or T = 1/f. It is constant. The on-time is the duration of the pulse voltage (t). The pulse duration can vary depending upon what the application is. If the period is 50 ms and the pulse on-time is 10 ms, the duty cycle (D.C.) is:

$$\text{D.C.} = 10/50 = 0.2 \times 100 = 20\,\%$$

Circuits can be made to change the on-time so that the duty cycle can be varied from a few percent to nearly 100%. This is called PWM. It was introduced earlier in the class D amplifier discussion. PWM is widely used in switching power supplies such as regulators and DC–DC converters.

Keep in mind that if you filter the pulses into an average proportional DC with a capacitor or LPF, you can vary the DC from some low value with a low duty cycle or some higher value with a higher duty cycle.

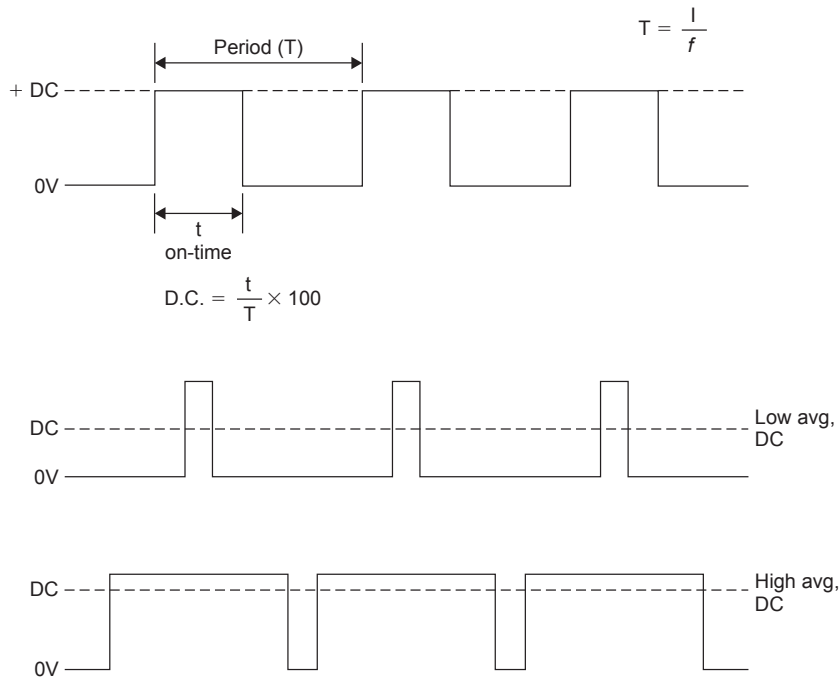


FIGURE 4.22 Concept of duty cycle and how varying pulse widths can be filtered into a proportional DC average voltage. *avg*, Average.

Linear regulators work very well but are not very efficient as they waste power in the series transistor. Typical efficiency is 10%–40%. A switching regulator is far more efficient as it is off for a large part of the time. Efficiencies in the 70%–95% range are common.

DC–DC Converters

A DC–DC converter is a circuit that does what its name implies. It translates one DC voltage to another. It can take the voltage from a 12-V battery and generate several hundred or thousand volts. Or it can take a 4.2-V battery and produce voltages of 3.3 or 2.5 V and 15 V. By building one DC power supply, several other output voltages can be obtained by using different DC–DC converters.

Bus-Oriented Architecture

Many power supplies have what we call a bus architecture. See Fig. 4.21. The DC power supply produces one main output voltage. That voltage is applied to a common DC bus. A bus is just the name for the two + and – DC lines that carry the voltage. Then, regulators and DC–DC converters are used to generate the voltages needed by the equipment. Again see Fig. 4.21.

Power Management

Many power supplies today include a circuit that manages the power supply voltages. It is usually a single IC that does things like turn on the various DC voltages in a power supply in a specific sequence. Some ICs require multiple DC voltages and they must be turned on one at a time in a specific sequence. In addition, the power management chip does things like monitor current usage. If one power supply is not being used, meaning current not being drawn from it, that part of the power supply is shut down to conserve power. A good example of this is the power management in a laptop computer or cell phone that monitors and controls all DC power to preserve the battery charge for longer life. Some other functions performed by power management chips are voltage monitoring with voltage alarm if a voltage fails, temperature monitoring, fault detection, over voltage or under voltage detection, and power control. Some power management chips also have the battery charging circuits built in. Every cell phone and laptop has one of these.

Inverters

An inverter is a power supply that converts DC into AC. A common unit converts 12 V from a car battery into standard 120 V 60 Hz AC. With an inverter you can operate common household lights and appliances from a battery.

A special variation of an inverter is the uninterruptible power supply (UPS). These are widely used with computers and networks to provide power even during loss of AC input from the power line. A battery operates an inverter that is used to power the computers and other equipment. If the AC power fails, the equipment continues to operate. The battery is continuously charged by a built-in battery charger that operates from the AC power line.

Solar Power System

Any home or business solar power system is similar to a large UPS (see Fig. 4.23). It uses the solar panels to charge a bank of batteries that store the energy for use later when the sun goes down. The inverters convert the DC into standard 120/240 V AC to power the house. In some cases, unused power is sent back to the power grid.

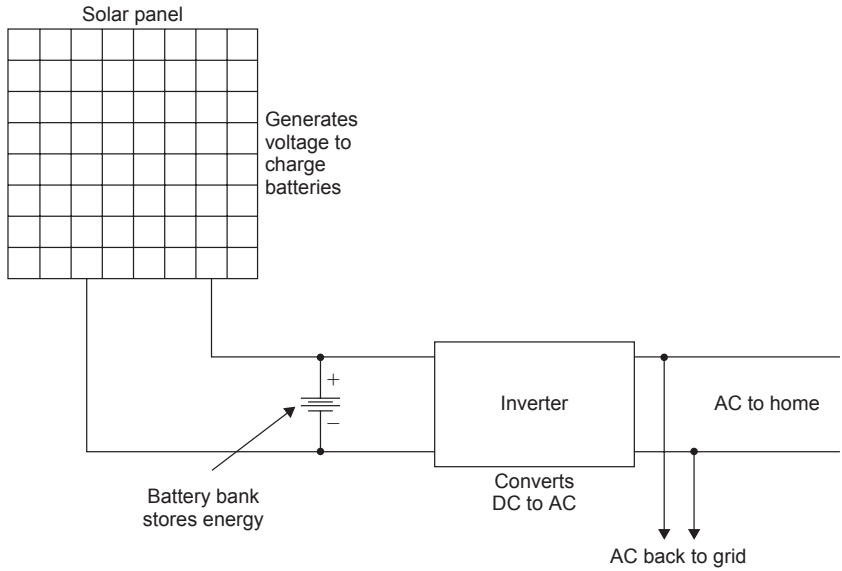


FIGURE 4.23 Common DC-to-AC solar power system.

Project 4.1

Build a Kit

If you are really serious about electronics, then one of the first things you should do is build a kit. A kit, in case you really do not know, is a complete package of electronic parts to make a specific product. You build it yourself by placing components on a printed circuit board and soldering them in place. There is no better way to see how electronic products get put together than to handle the wide variety of parts. It is a great learning experience.

There are two main questions to answer about this project. First, what kind of kit do you want? Second, can you learn to solder? You will have to answer the first question, but as for the second, yes, you can learn to solder. It's not that hard. You can learn in Chapter 14.

One way to get an overview of the kits available is to obtain print catalogs (if available) from the sources listed below. You can order a print copy online and see the whole range of kits available. Go to:

Adafruit: www.adafruit.com
All Electronics: www.allelectronics.com
Digi-Key: www.digikey.com
Jameco: www.jameco.com
Mouser: www.mouser.com
SparkFun: www.sparkfun.com
Velleman: www.velleman.com

What I recommend is to get a kit related to one of the topics in this chapter. A power supply is a great choice, and it will give you a variable DC voltage source that you can use in future projects. I recommend the Jameco dual variable supply

Project 4.1—cont'd

kit 20626. Most of the companies have lots of radio- and wireless-related kits, but save these for the later chapters on wireless products.

Don't forget to get a small soldering iron (25W or so) with a small tip and some solder. You will also need a few hand tools such as a wire stripper, needle-nose pliers, side cutters, and a small screwdriver, if you do not already own these. See Chapter 14.

Project 4.2

Getting Familiar With Virtual Instruments and the Oscilloscope

To really appreciate how electronic circuits work, you need a way to look at the voltages inside and outside circuits. To do that, you need an oscilloscope (scope). This is a test instrument that displays signal voltages, analog or digital, versus time on a screen. It allows you to measure voltage, frequency and time on the display. Using the probes supplied you can observe input and output signals and unique waveforms going on inside the circuit. Scopes are ideal for design and testing or for troubleshooting and repair.

Oscilloscopes are relatively expensive bench instruments. However, today you can have an oscilloscope for a few hundreds of dollars. It is part of a product known as a virtual instrument (VI). A VI is a small package of hardware that connects to the signals to be observed plus a PC or laptop computer. The laptop runs software that implements the oscilloscope functions and the LCD video monitor is the display.

Some VI products are just an oscilloscope such as the one shown in Fig. 4.24. Another version of this product also contains a signal generator that produces

FIGURE 4.24 The Velleman PCSU1000 oscilloscope. It has dual channels for observing two signals at once and a bandwidth of 60 MHz. *Photo courtesy of Velleman.*

Continued

Project 4.2—cont'd

variable frequency sine, square, and other waves you can use as inputs to test circuits and equipment.

Another type of VI is more of a complete instrument package. In addition to the scope and generator, these units also contain DC power supplies and other instruments such as a digital multimeter (DMM). Software implements the instruments, and the laptop displays the output and controls. Two such units are shown in Fig. 4.25. On the left (A) is National Instruments' myDAQ. On the right (B) is the Digilent Analog Discovery 2. Both contain a scope, generators and power supplies. For more details on these and the Velleman units, go to the manufacturers' websites. Other similar products are available.

Digilent: www.diligent.com
National Instruments; www.ni.com
PicoScope: www.picotech.com
Velleman: www.velleman.com

If you are going to be a serious hobbyist or DIY maker, it is strongly recommended that you acquire one of these units. The projects that follow assume that you have one of these units or the equivalent.

To wrap up this project, do the following:

1. Buy one of the units suggested above or an equivalent.
2. Install the unit and software.
3. Read the instruction manual.
4. Demonstrate the scope function by observing the sine output of the internal signal generator.

FIGURE 4.25 Virtual instrument units. Left: National Instruments' myDAQ, Right: Digilent Analog Discovery 2. *Photos courtesy of National Instruments and Digilent.*

Project 4.3

Build a Power Supply

You will need two power supplies for the projects that follow in this and later chapters. If you built a power supply kit as recommended in Project 4.1, you are all set. Or you can use batteries. The four AA cell source you built earlier is excellent but you will need a second one for some projects. You can also use the 9-V battery. Get a second 9-V battery and clip for some projects. Another choice is to get one of the wall adapter supplies. Choose the AC to DC type with 5- or 9-V output. The regulated versions are best and have a cleaner output. The current rating should be 0.2 A or more. See the parts list in Appendix B.

If you acquired one of the VI products such as the myDAQ or Analog Discovery 2, you can probably use the internal supplies. The circuits to be demonstrated will indicate the voltage options to use.

For this project, do the following:

1. Acquire what you need.
2. Test the supplies with your DMM (measure output voltages).

Project 4.4

Build a Signal Source

For some projects you will need a signal source to use as an input signal. A sine wave is best. Some projects such as the digital circuits in Chapter 5 need a rectangular/square wave signal. If you bought one of the VI units with a signal generator, you are ready to go. If not, here are a couple of options.

An easy choice is to use the 60-Hz or 50-Hz power line AC as a signal. Use a transformer to step the voltage down to a safe lower level then use a potentiometer to adjust the output to a suitable value. A safe choice is to use an AC to AC wall adapter transformer with a 5-V output. Cut off the connector on the cable then strip the wires and tin them with solder so they plug into the breadboard. (Note: You may need to solder the transformer wires to solid #22 hookup wire if they do not plug into the breadboarding socket holes.) Connect the wires to a 1-kΩ potentiometer as a voltage divider. See Fig. 4.26. See the parts list in Appendix B.

A more complex generator is the one shown in Fig. 4.27. It uses the 555 timer IC. This popular chip generates rectangular pulses at a frequency set by resistors R_1 and R_2 and C_1. You can build this circuit on your breadboarding socket. The parts list in Appendix B.

Before you tackle this project, look at Fig. 4.28 which is a review of breadboard specifics. Look this over carefully before you build the circuit. Keep in mind that there is no specific layout for a circuit. You build it up as you go along. For this circuit, build it on one end of the breadboarding socket so that you will have room for other circuits to be built later. Here are some other guidelines:

- Use #22 solid insulated hookup wire for direct point to point connections.
- Integrated circuits are to be mounted so that they straddle the center area between the two groups of holes. See Fig. 4.28.

Continued

Project 4.4—cont'd

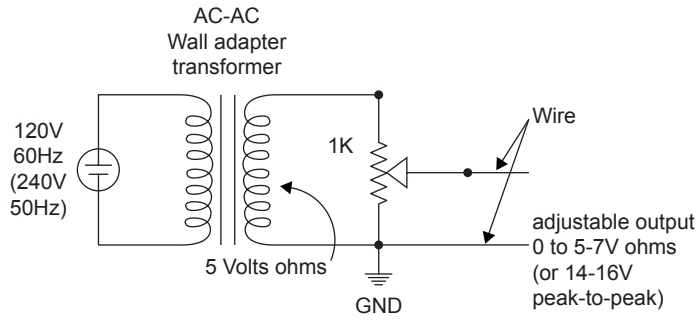


FIGURE 4.26 An AC–AC wall adapter transformer and a pot form a variable 60 (50) Hz signal source.

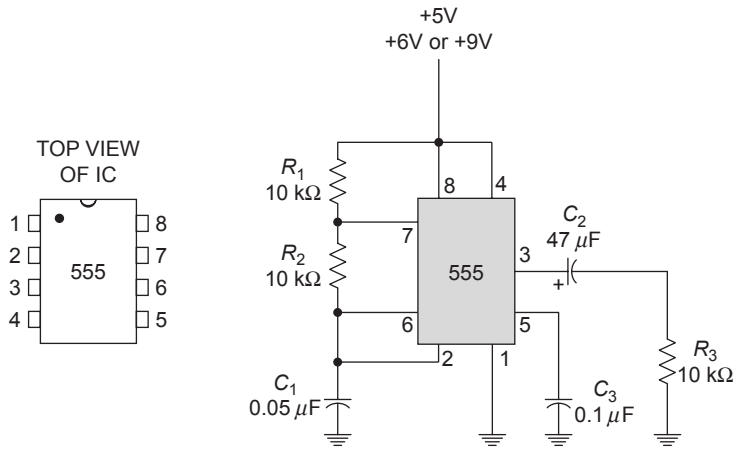


FIGURE 4.27 A 555 timer IC circuit that generates rectangular waves.

- Be sure to pay attention to the IC orientation and pin numbers. See Fig. 4.27 for details.
- Some capacitors such as the electrolytics and tantalums are polarity sensitive. Make sure the + or – leads are wired as the schematic shows or damage will result.
- If you are still unsure about how to build the circuit on the breadboard, do an internet search on "how to use a breadboard." You will find YouTube videos and many other tutorials to help you. However, the best way to do this is just dive in and give it a try correcting as you go along.

Once you have built one or more of the circuits, you will test them in Project 4.5.

Project 4.4—cont'd

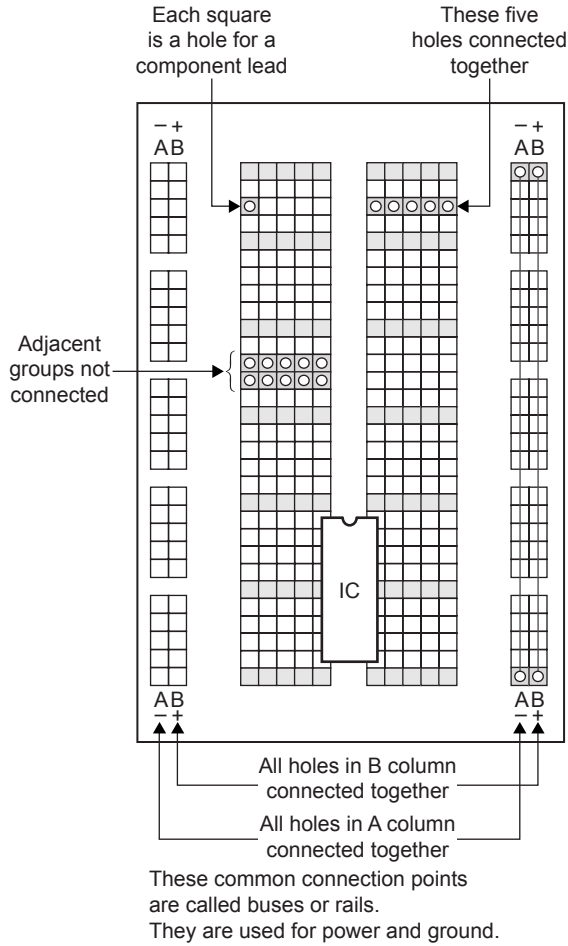


FIGURE 4.28 One type of breadboarding socket. Not all sockets have the A and B power and ground buses in which case you can designate any one group of 5 pins to power and another for ground.

Project 4.5

Testing Circuits With an Oscilloscope

Before you test the circuits you built in the previous project, you need to familiarize yourself with the oscilloscope itself. Read the manual first. Then power up the scope and be sure the screen is displayed on the video monitor. The scope screen should look something like that shown in Fig. 4.29. The screen is a grid of horizontal and vertical lines. The horizontal scale is time and the vertical scale is volts. Each of the grid's major segments represents a calibrated value. Horizontal grid increments are usually in milliseconds or microseconds per division such as 5 milliseconds (ms) per division. The vertical grid is calibrated in millivolts or volts. For example, one setting may be 5V per division. See Fig. 4.29 for clarification. The scope lets you change these settings so you can adjust it to view a wide range of signals. Check the scope instructions to be sure you know how to do this. Because the grid is calibrated you can measure the time period (t) of a

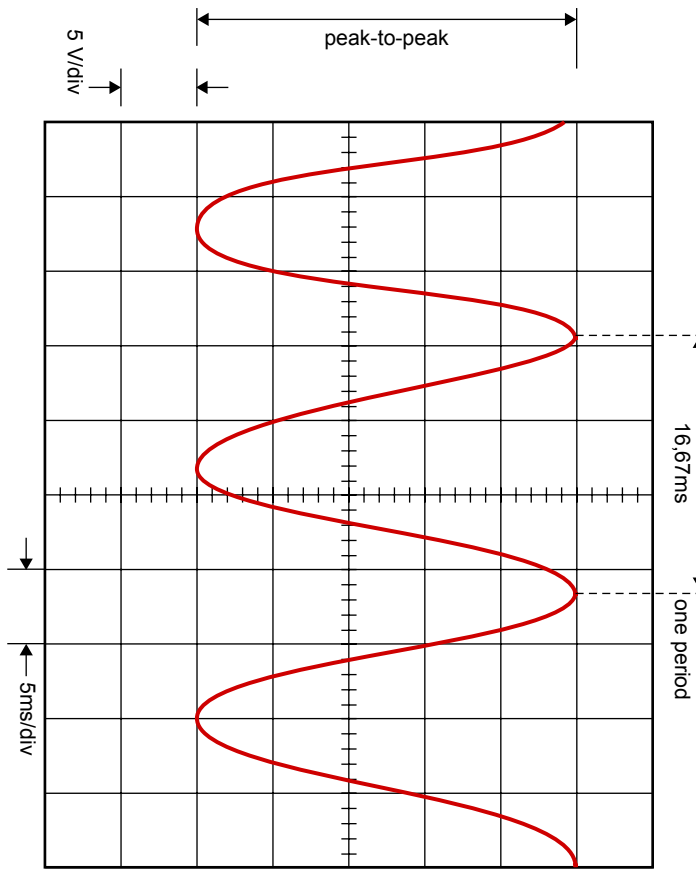


FIGURE 4.29 A 60-Hz sine wave displayed on an oscilloscope.

Project 4.5—cont'd

signal and its voltage amplitude. Remember if you know the period of a signal (t), you can calculate the frequency (f) with the formula f = 1/t. Now on to the testing.

If you built the simple signal source as shown in Fig. 4.26, get it ready and turn on your oscilloscope, and set the horizontal and vertical scales to those shown in Fig. 4.29. Follow these steps:

- Plug the wall adapter transformer into an AC outlet.
- Connect short hookup wires (2 or 3 inches) to the pot on the breadboarding socket. One wire is connected to ground, and the other to the slider arm of the pot (usually the center pin). These wires will let you connect the scope probe inputs to the circuit. See Fig. 4.26. Some VIs may have other arrangements so follow the guidelines in the VI manual.
- Rotate the pot knob to the maximum clockwise (CW) position.
- Connect the scope to the pot output. You should see a sine wave as shown in Fig. 4.29. Make adjustments as needed to see all of the signal.
- If you do not see a signal, rotate the pot to the maximum counter clockwise position (CCW).
- Now measure the period of the sine wave between two successive peaks. Each major division is 5 ms so each smaller increment is 1 ms. For a 60-Hz sine wave the period is 16.67 ms. You should be able to estimate that from the display.
- Next measure the peak-to-peak amplitude of the signal. This is the voltage between the maximum positive peak and maximum negative peak. If you bought a 5-V transformer, the peak should be 14–16V. The 5-V rating is an rms value and the peak-to-peak value 2.828 or more times the rms value.
- Now vary the pot knob from maximum CW to CCW positions and note how the sine wave amplitude varies from zero to its maximum value. This lets you set the voltage as you need.
- Unplug the transformer.

If you built the circuit in Fig. 4.27, check your wiring and get ready for the test. Do this:

- Apply DC power. The circuit is flexible so you can use what DC voltage you have from about 4.5–15V. Your 5-, 6-, or 9-V supplies will work ok.
- Set up the scope. Some recommended settings are 0.5 or 1V per division vertically and 200 or 500 ms per division horizontally.
- Connect the scope input to the top of the 10-k resistor R3 and ground. You should see a signal like that in Fig. 4.30. This figure assumes a power supply voltage of 6V. Adjust the scope setting to display the signal as in the figure.
- Measure the period and peak-to-peak values. The p–p value should be a bit less than the DC supply voltage. With resistor and capacitor values shown, the frequency computes to 962 Hz. That is close to 1000 Hz or 1 kHz. The period should be little bit more than 1 ms between consecutive positive or negative going edges of the pulses.
- Disconnect the power.

Continued

Project 4.5—cont'd

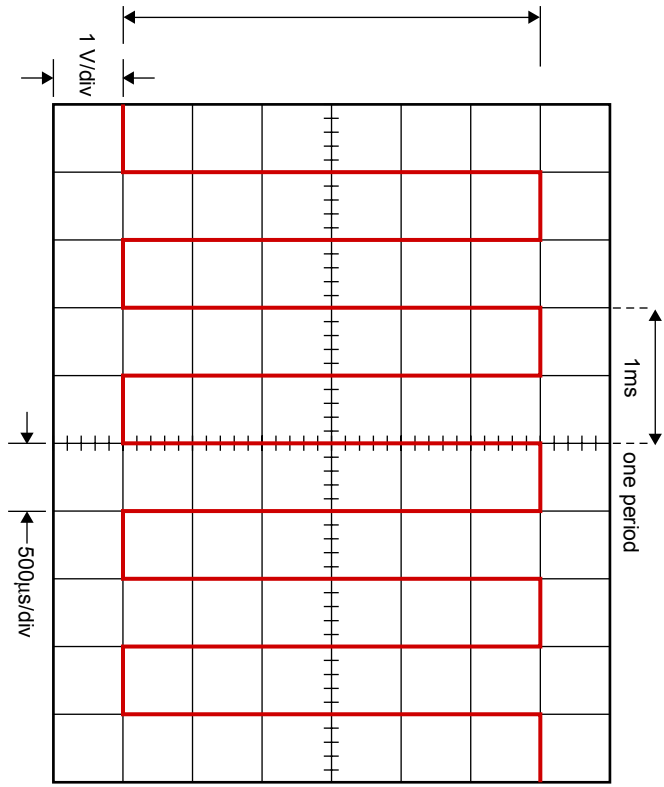


FIGURE 4.30 The output of the 555 timer circuit displayed on an oscilloscope.

A Word About Troubleshooting

If your circuit does not work, you will need to troubleshoot it. Here are a few suggestions.

- The problem is most likely a wiring error. Check all of your connections carefully. Rewire as needed. A common mistake is plugging a component leads into the wrong adjacent hole. Refer back to Fig. 4.28 for a review.
- Be sure that the right part is in the right position. Double check resistor color code values. If polarized capacitors are used, be sure the + and – leads are in the designated position.
- Use your DMM to see that the circuit is getting DC power. Measure between pins 1 and 8.
- If the 555 timer circuit of Fig. 4.27 does not work again, check the wiring. Try rewiring according to that in Fig. 4.28 and try testing again.
- If available, a knowledgeable friend or acquaintance may be able to help.

Project 4.6

Experimenting With the 555 Timer

The 555 timer IC is a very versatile device. Here are several different uses to try.

- Remove the 10-kΩ resistor R3 from the circuit in Fig. 4.27 and replace it with an 8-Ω speaker and 100-Ω resistor. See Fig. 4.31.
- Apply DC power. You will hear the 962-Hz audio tone in the speaker.
- Turn off the power.
- Rewire the circuit so that it is like that shown in Fig. 4.32. You will replace the 0.05-μF capacitor with the 47-μF capacitor. Be sure to observe the correct polarity. Then connect the 220-Ω resistor and LED as shown to replace the speaker. Again be sure to orient the LED correctly as shown.
- Apply power. The LED should blink at an approximate rate on once per second.
- Turn off the power.
- Turn off the power but do not disassemble the 555 circuit as you will use it in Chapter 5.

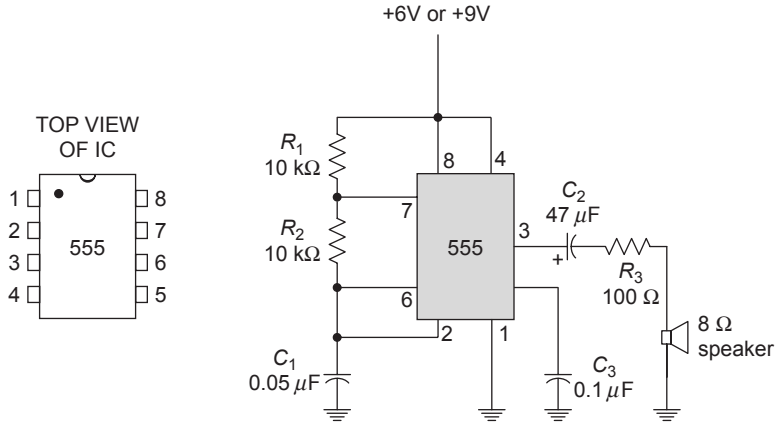


FIGURE 4.31 The 555 IC connected as an audio tone generator with speaker.

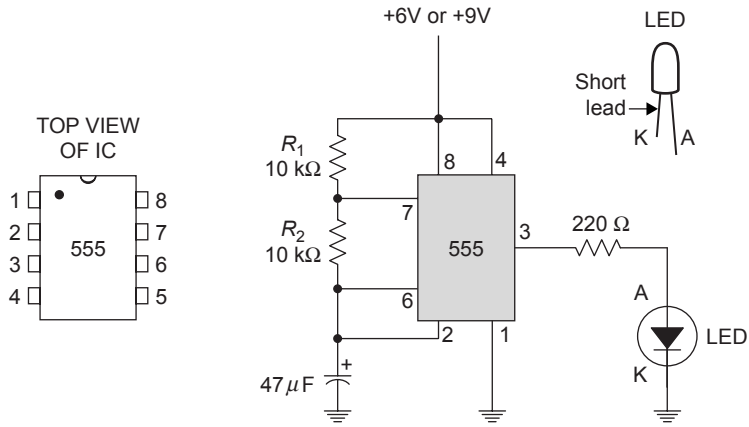


FIGURE 4.32 The 555 IC connected to flash an LED off and on.

Project 4.7

Building a Half Wave Rectifier and Power Supply

A rectifier is a diode that converts AC into pulsating DC. Rectifiers are a part of most power supplies. Here you will demonstrate how a diode produces half sine pulses that can then be filtered into a steady DC. By adding an IC voltage regulator you will create a useful power supply you can use in later projects.

- Remove the 1-k pot from the wall adapter transformer in Fig. 4.26 and wire the circuit in Fig. 4.33. Add only the 1N4001 diode and 1-k-Ω resistor at this time.
- Plug the transformer into an AC outlet. Connect the oscilloscope to the 1-k resistor output. You should see half sine pulses like that in Fig. 4.34. The peak pulse value should be about 7–9V with a 5V transformer.
- Measure the voltage across the 1-k resistor with your DMM. It is the DC average voltage of about 2–4V with the 5V transformer.
- Now connect a 1000 µF capacitor across the 1 k resistor as shown in Fig. 4.33. Be sure to get the polarity right as shown.
- Measure the voltage across the capacitor with your DMM. This is the DC average voltage with peaks of about 7–9V with the 5-V transformer. The capacitor filters out the pulses into a steady DC.
- When you connected the 1000 µF, you noticed that the pulses went away on the scope screen. There will still be some minor variations on the output called ripple. It will be only a few millivolts or less. You can see it on the scope if you change the vertical sensitivity.

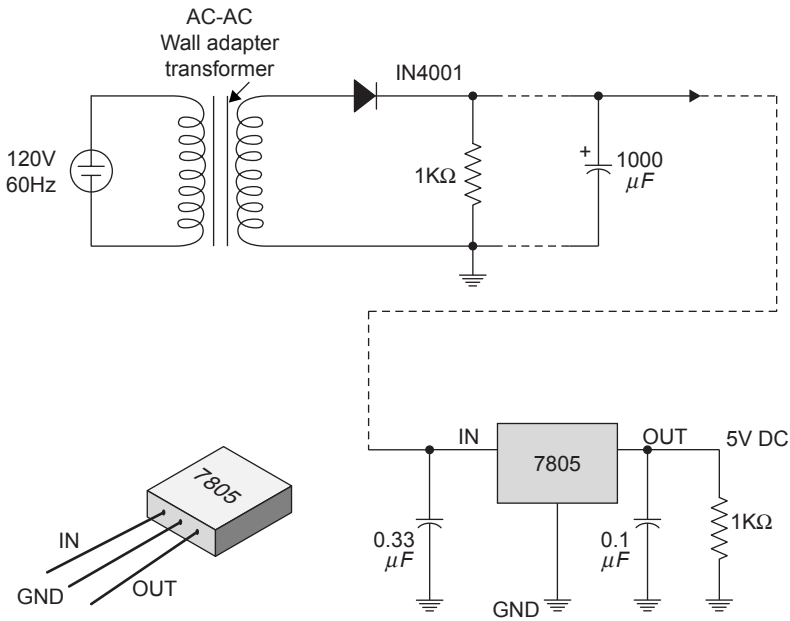


FIGURE 4.33 A half wave rectifier and regulated 5-V power supply.

Project 4.7—cont'd

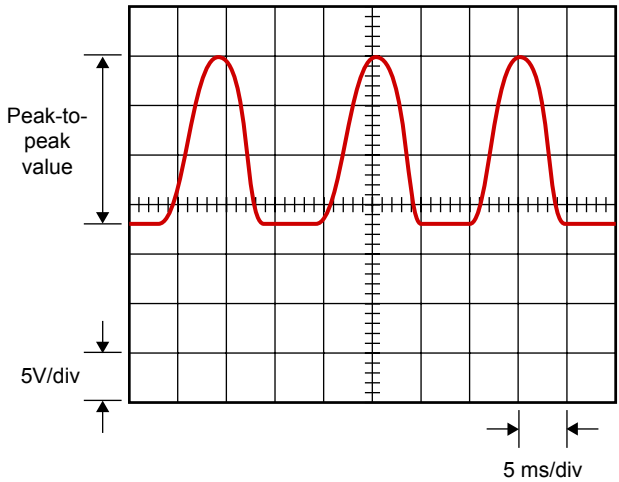


FIGURE 4.34 The half sine pulses as seen on the oscilloscope.

- Next, connect a 7805 IC regulator to the output as shown in Fig. 4.33. This IC converts the voltage across the 1000-μF capacitor into a stable and accurate 5V.
- Measure the output across the 1-k-Ω resistor with your DMM.
- Unplug the transformer.

Project 4.8

Experimenting With Operational Amplifiers

An op amp is an all-purpose amplifier that can be connected in a variety of ways to meet many amplification needs. Most op amps require two power supplies, one positive and the other negative. With two supplies the output voltage swing can be positive and negative. Fig. 4.35 shows the most common op amp configuration. This is an inverting amplifier. See Fig. 4.8 and the related text for a review. Note how the power supplies are connected to pins 7 and 4. You can use two 5-volt supplies, the 6-V AA cell supplies, or two 9-V batteries or the supplies in your VI device. The junction of the two supplies is the circuit ground.

Wire the circuit of Fig. 4.35 on the breadboard. The 1-k pot is connected to the positive supply to provide a variable DC voltage to use as an amplifier input. Double check your wiring before you go to the procedure below.

- Apply voltage to the circuit. Use your DMM to check for voltages on pins 7 and 4 on the IC.
- Measure the pot output voltage and vary the pot to set its output to 1V. Connect the +1V to the op amp as shown in the figure.

Continued

Project 4.8—cont'd

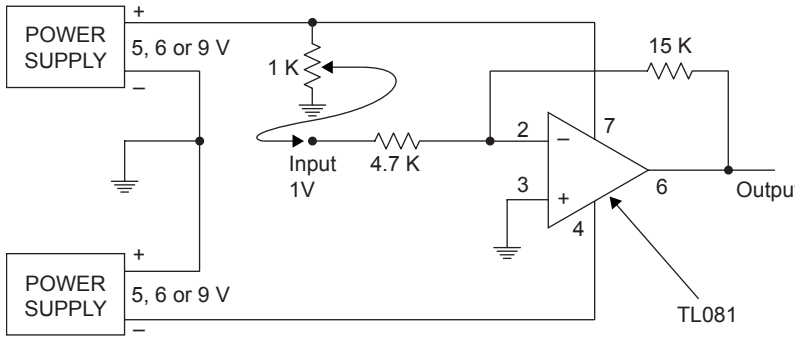


FIGURE 4.35 Operational amplifier inverter circuit showing power supply detail.

- Using the resistor values given in the figure, calculate the circuit gain.
- Calculate the value of the output voltage given the 1-V input.
- Now measure the op amp output at pin 6 with your DMM. You should get −3.2V. The circuit gain is 15 k/4.7 k = 3.2 so with 1V in you will get −3.2V out. The voltage is negative because the op amp inverts the + input. Op amps can amplify DC and well as AC signals.
- Turn off the power and rewire the circuit as shown in Fig. 4.36. This is a non-inverting amplifier.
- Use the formula in Fig. 4.8 to calculate the gain using the resistor values given (see Fig. 4.8).
- Connect an input signal to the op amp at pin 3. Use the 60-Hz output from the circuit in Fig. 4.26. Disconnect the wall transformer from the power supply you built in Project 4.7 and connected to the 1-k ohm pot as shown in Figs. 4.26 and 4.36.
- Using the scope, set the output of the 1-k pot to 1V peak-to-peak. Connect the pot output to pin 3 of the op amp. Now look at the output at pin 6 of the op amp with the scope. Since the calculated gain is 6.8 k/1 k + 1 = 7.8, the output should be 7.8V peak-to-peak.
- While observing the output on pin 6 of the op amp, rotate the 1-k pot to increase the input voltage. At some point, you will see the output sine wave increase until the output saturates and clips creating a square wave. The output voltage cannot be greater than the power supply voltages.
- Disconnect power.

Project 4.8—cont'd

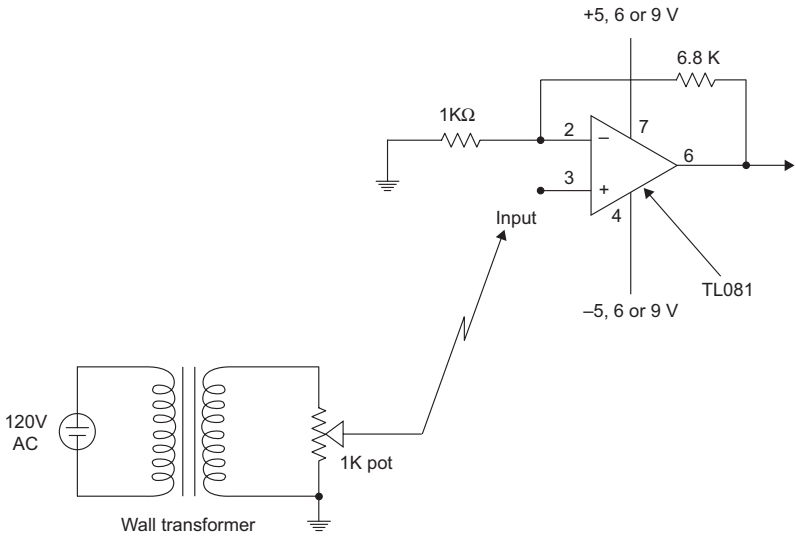


FIGURE 4.36 Operational amplifier noninverting amplifier circuit.

Project 4.9

Try Out a Circuit Simulator

A circuit simulator is a software program that lets you build an electronic circuit and test it on your computer. A schematic capture program helps you construct the circuit on screen using built-in component symbols and wiring. The software then converts that circuit into a sequence of operations that simulate the various components and the operation of the circuit. Built-in waveform viewers and read out capability lets you see how the circuit works and performs. Electronic engineers regularly use simulators to help design circuits and evaluate them before constructing physical prototypes and before committing to an expensive IC design. Some simulators are accompanied a PCB layout program that helps you design a PCB for your circuit.

Circuit simulators require some learning time but they are worth the effort. You can also substitute a circuit simulator for the actual hands-on projects in this book, although that is not recommended. Use the simulators to complement the real lab work projects.

Listed below are several circuit simulators to try. Some are free while others require payment to access.

https://circuits.io/

https://www.circuitlab.com/editor/#?id=7pq5wm

Continued

Project 4.9—cont'd

http://dcaclab.com/en/home
http://www.docircuits.com/circuit-editor
http://everycircuit.com/
http://www.partsim.com/simulator
http://www.schematics.com/

Recommended action:

- Try out one or more circuit simulators listed. Build and test at least one circuit.
- Implement one or more of the hardware projects you experimented within this chapter. The 555 timer, half wave rectifier and op amp projects are suggested.
- Compare your hands-on results with the simulated results.

Chapter 5

Electronic Circuits: Digital

Practically Everything Is Digital These Days

In this Chapter:

- Binary number system.
- Logic gates and flip-flops.
- Common combinational and sequential circuits.
- Semiconductor memory.
- Programmable logic devices.
- Analog-to-digital and digital-to-analog conversion.

INTRODUCTION

Recall that there are two basic types of electronic signals—analog and digital. A digital signal is one that varies in discrete steps. Unlike an analog signal, which varies continuously, a digital signal has two levels or states. The signal switches or changes abruptly from one state to the other.

Fig. 5.1 shows a DC digital signal that switches between two known levels such as 0 V and close to it (0.1 V) or 0 and 3.3 V. The positive voltage can be anything between about 1 and 12 V with 3.3 and 5 V being the most common.

Digital signals with two discrete levels are also referred to as *binary signals. Binary* means two—two states or two discrete levels of voltage.

Humans use the decimal number system that represents quantities with digits 0 through 9. However, digital equipment and computers do not. Internally, digital equipment processes binary data.

BINARY NUMBERS

The binary number system is a set of rules and procedures for representing and processing numerical quantities in digital equipment. Because the base of the binary number system is 2, only two symbols (0 and 1) are used to represent any quantity. The symbols 0 and 1 are called *binary digits* or *bits*. For example, the 6-bit number 101101 represents the decimal number 45. Your understanding of

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00005-9
Copyright © 2018 Elsevier Inc. All rights reserved.

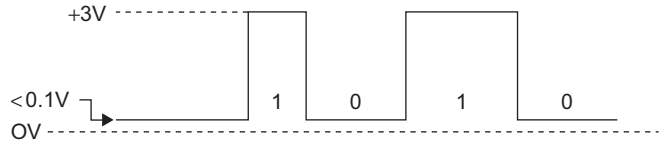


FIGURE 5.1 Binary signal that represents 0 and 1 as voltage levels.

how digital circuits, microprocessors, and related equipment process data is tied directly to an understanding of the binary number system.

The reason for using binary numbers in digital equipment is the ease with which they can be implemented. The electronic components and circuits used to represent and process binary data must be capable of assuming two discrete states to represent 0 and 1. Examples of two-state components are switches and transistors. When a switch is closed or on, it can represent a binary 1. When the switch is open or off, it can represent a binary 0. A conducting transistor may represent a 1, whereas a cutoff transistor may represent a 0. The representation may also be voltage levels. For example, a binary 1 may be represented by +3.3 V and a binary 0 by 0 V as previously shown in Fig. 5.1.

Binary-to-Decimal Conversions

The binary system is similar to the decimal system in that the position of a digit in a number determines its weight. Recall that in the decimal system the weights are powers of 10. The rightmost digit is units or 1s and then 10s, 100s, 1000s, and so on, moving from right to left from one digit to the next. The position weights of a binary number are powers of 2:

$2^0 = 1$
$2^1 = 2$
$2^2 = 4$
$2^3 = 8$
$2^4 = 16$
$2^5 = 32$
$2^6 = 64$
$2^7 = 128$
$2^8 = 256$

The position weights of an 8-bit binary number are as follows:

Bit position	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Weight	128 (MSB)	64	32	16	8	4	2	1 (LSB)

The most significant digit or bit (MSB) and the least significant bit (LSB) are identified.

Now let us evaluate the decimal quantity associated with a given binary number, 101101. You simply multiply each bit by its position weight and add the values to get the decimal equivalent, 45.

Position weight	32	16	8	4	2	1
Binary number	1	0	1	1	0	1

1 × 1	=	1
0 × 2	=	0
1 × 4	=	4
1 × 8	=	8
0 × 16	=	0
1 × 32	=	32
Decimal equivalent		45

You can see that positions with a 0 bit have no effect on the value. Therefore, they can be ignored. To quickly determine the decimal equivalent of a binary number, simply sum the weights of the positions containing a 1 bit. For example, in the number 11101, the weights of those positions with a 1 bit from right to left are 1 + 4 + 8 + 16 = 29.

Using Hardware to Represent Binary Quantities

Switches are widely used to enter binary data into computers and digital equipment. If the switch is set to the up position, a binary 1 is represented. If the switch is down, a binary 0 is represented. The switch contacts can be opened or closed depending on the circuit in which the switch is connected. Fig. 5.2 shows a group of slide switches set to represent a binary number, 11000101 or 197.

Indicator lights such as light-emitting diodes (LEDs) are sometimes used to read out binary data in digital equipment. An "on" light is a binary 1 and an "off" light is a binary 0. See Fig. 5.3. The decimal value being represented by the display is 178.

Decimal-to-Binary Conversions

You may find it necessary to convert decimal numbers into their binary equivalents. This can be done by dividing the decimal number by 2, dividing the quotient by 2, dividing that quotient by 2, and so on, recording the remainders until the quotient is zero. The remainders form the binary equivalent.

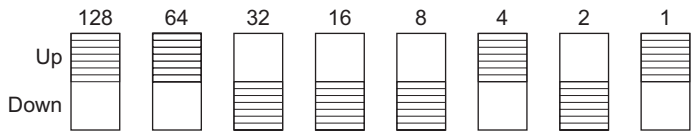


FIGURE 5.2 Off/on switches are used to enter binary data into digital circuits.

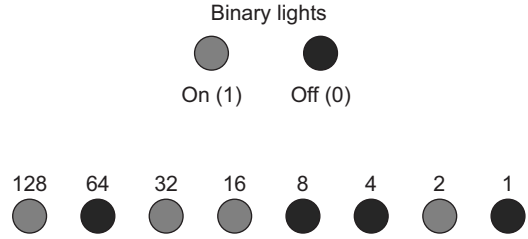


FIGURE 5.3 How lights or LEDs are used to represent binary data.

In the following example, we convert the decimal number 57 to its binary equivalent.

Quotient	Remainder
57 ÷ 2 = 28	1 (LSB)
28 ÷ 2 = 14	0
14 ÷ 2 = 7	0
7 ÷ 2 = 3	1
3 ÷ 2 = 1	1
1 ÷ 2 = 0	1 (MSB)

You can always check your work by reconverting the binary number back to decimal using the procedure described earlier. Also, keep in mind that some scientific calculators can do binary-to-decimal and decimal-to-binary conversions.

Another name for a binary number is *binary word*. The term *word* is more general. It refers to a fixed group of bits that can mean numbers, letters, or special characters and codes. We say that digital equipment processes *binary data words*.

All digital circuits and microcomputers work with a fixed-length binary word. A common binary word length in microcomputers and other digital equipment is 8 bits. All data storage, processing, manipulation, and transmission are carried out in 8-bit groups. Word lengths of 4, 8, 12, 16, 32, and 64 bits are common in digital equipment.

An 8-bit word is usually called a *byte*. In data communication applications, an 8-bit word is sometimes called an *octet*. A 4-bit word is sometimes referred to as a *nibble*.

Maximum Decimal Value for N Bits

The number of bits in a binary word determines the maximum decimal value that can be represented by that word. This maximum value is determined with the formula:

$$M = 2^N - 1$$

where M is the maximum decimal value and N is the number of bits in the word.

TABLE 5.1 Number of Bits in Binary Number and Maximum Number of States

Number of Bits	Maximum States
8	256
12	4096 (4 K)
16	65,536 (64 K)
20	1,048,576 (1 M)
24	16,777,216 (16 M)
32	4,294,967,296 (4 G)

G, gigabits = 1,0737,41,824; *K*, kilobits = 1024; *M*, megabits = 1,048,576.

For example, what is the largest decimal number that can be represented by 4 bits?

$$M = 2^N - 1 = 16 - 1 = 15$$

With 4 bits, the maximum possible number is binary 1111 or decimal 15.

The maximum decimal number that can be represented with 1 byte is 255 or 11111111. An 8-bit word greatly restricts the range of numbers that can be accommodated. But this is usually overcome by using larger words.

There is one important point to know before you leave this subject. The formula $M = 2^N - 1$ determines the maximum decimal quantity (M) that can be represented with a binary word of N bits. This value is 1 less than the maximum number of values that can be represented. The maximum number of values that can be represented (Q) is determined with the formula:

$$Q = 2^N$$

With 8 bits, the maximum number of values is 256 or 0 through 255.

Table 5.1 gives the number of bits in a binary number and the maximum number of states that can be represented.

BCD and ASCII

The binary numbers we have been discussing are usually referred to as pure binary codes. But there are other types of binary codes. For example, the binary-coded decimal (BCD) system is popular. BCD is a hybrid code between the binary and decimal systems. It was developed in an attempt to simplify the conversion processes between the two systems and to improve human–machine communication.

TABLE 5.2 Binary-Coded Decimal

Decimal Value	BCD Code
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001

To represent a decimal number in the BCD system, each digit is replaced by its 4-bit binary equivalent. Thus, the number 729 in BCD is:

7 2 9

0111 0010 1001

The BCD code is given in Table 5.2.

It is important to note that the 4-bit binary numbers 1010 through 1111 that represent the decimal values 10 through 15 are invalid in BCD.

To convert a BCD number to decimal, simply substitute the decimal equivalent of each 4-bit group. The BCD number 1001 0100 0110 in decimal is 946.

A special form of BCD code is used in computers and data communications systems. It is a 7- or 8-bit code that is used to represent not only numbers but also letters (both uppercase and lowercase), special symbols, and control functions. This code is called the American Standard Code for Information Interchange, or ASCII (pronounced "ask-key").

The following are examples of ASCII:

Number, letter, or symbol	ASCII
F	01000110
8	00111000
J	01101010
+	00101011

The complete ASCII is given in Table 5.3. It provides the decimal and hexadecimal (hex) values of the codes. The code contains both uppercase and lowercase letters, the digits 0 through 9, punctuation marks, common mathematical

TABLE 5.3 The ASCII Character Code

Char	Dec	Oct	Hex	Char	Dec	Oct	Hex	Char	Dec	Oct	Hex	Char	Dec	Oct	Hex
(nul)	0	0000	0300	(sp)	32	0040	0320	@	64	0100	0340	′	96	0140	0360
(soh)	1	0001	0301	!	33	0041	0321	A	65	0101	0341	a	97	0141	0361
(stx)	2	0002	0302	“	34	0042	0322	B	66	0102	0342	b	98	0142	0362
(etx)	3	0003	0303	#	35	0043	0323	C	67	0103	0343	c	99	0143	0363
(eot)	4	0004	0304	$	36	0044	0324	D	68	0104	0344	d	100	0144	0364
(enq)	5	0005	0305	%	37	0045	0325	E	69	0105	0345	e	101	0145	0365
(ack)	6	0006	0306	&	38	0046	0326	F	70	0106	0346	f	102	0146	0366
(bel)	7	0007	0307	’	39	0047	0327	G	71	0107	0347	g	103	0147	0367
(bs)	8	0010	0308	(	40	0050	0328	H	72	0110	0348	h	104	0150	0368
(ht)	9	0011	0309	)	41	0051	0329	I	73	0111	0349	i	105	0151	0369
(nl)	10	0012	030a	*	42	0052	032a	J	74	0112	034a	j	106	0152	036a
(vt)	11	0013	030b	1	43	0053	032b	K	75	0113	034b	k	107	0153	036b
(np)	12	0014	030c	,	44	0054	032c	L	76	0114	034c	l	108	0154	036c
(cr)	13	0015	030d	2	45	0055	032d	M	77	0115	034d	m	109	0155	036d
(so)	14	0016	030e	.	46	0056	032e	N	78	0116	034e	n	110	0156	036e
(si)	15	0017	030f	/	47	0057	032f	O	79	0117	034f	o	111	0157	036f
(dle)	16	0020	0310	0	48	0060	0330	P	80	0120	0350	p	112	0160	0370
(dc1)	17	0021	0311	1	49	0061	0331	Q	81	0121	0351	q	113	0161	0371
(dc2)	18	0022	0312	2	50	0062	0332	R	82	0122	0352	r	114	0162	0372
(dc3)	19	0023	0313	3	51	0063	0333	S	83	0123	0353	s	115	0163	0373

Continued

TABLE 5.3 The ASCII Character Code—cont'd

Char	Dec	Oct	Hex	Char	Dec	Oct	Hex	Char	Dec	Oct	Hex	Char	Dec	Oct	Hex
(dc4)	20	0024	0314	4	52	0064	0334	T	84	0124	0354	t	116	0164	0374
(nak)	21	0025	0315	5	53	0065	0335	U	85	0125	0355	u	117	0165	0375
(syn)	22	0026	0316	6	54	0066	0336	V	86	0126	0356	v	118	0166	0376
(etb)	23	0027	0317	7	55	0067	0337	W	87	0127	0357	w	119	0167	0377
(can)	24	0030	0318	8	56	0070	0338	X	88	0130	0358	x	120	0170	0378
(em)	25	0031	0319	9	57	0071	0339	Y	89	0131	0359	y	121	0171	0379
(sub)	26	0032	031a	:	58	0072	033a	Z	90	0132	035a	z	122	0172	037a
(esc)	27	0033	031b	;	59	0073	033b	[	91	0133	035b	{	123	0173	037b
(fs)	28	0034	031c	,	60	0074	033c	\	92	0134	035c	|	124	0174	037c
(gs)	29	0035	031d	5	61	0075	033d	]	93	0135	035d	}	125	0175	037d
(rs)	30	0036	031e	.	62	0076	033e	^	94	0136	035e	~	126	0176	037e
(us)	31	0037	031f	?	63	0077	033f	_	95	0137	035f	(del)	127	0177	037f

Char, character; *Dec*, Decimal; *Hex*, Hexadecimal (4-bit groups); *Oct*, Octal (3-bit groups).
Characters in parentheses are control codes for specific operations.
X, "Don't care" character
Example: ASCII capital letter A

Decimal 65
Binary 0000000001000001
Octal 0/000/000/001/000/001
0 0 1 0 1
Hex 0000/0000/0100/0001
0 x 4 1

symbols, and many special two- and three-letter codes. The special codes are known as control codes. They are used to indicate the start and end of a string of characters or to initiate special operations. Some examples are as follows:

STX—Start of text sequence
EOT—End of transmission of a string of characters
BEL—Ring a bell
DEL—Delete
LF—Line feed
CR—Carriage return

These codes not only represent alphanumeric data but can also make things happen in a printer or computer.

The main use of ASCII is in data communication. Computers use ASCII to "talk" to their peripheral units, such as printers, or to one another. A common example is a personal computer that receives data via a modem from the Internet. Another example is the data sent from a computer to a laser printer. ASCII is the communication code for text.

Hexadecimal Notation

Hexadecimal notation is a way to represent binary values with numbers and letters in an effort to make data easier to remember and to reduce the errors normally associated with writing or reading long strings of 1s and 0s. The hex code is just an extension of the BCD code, with the decimal values from 11 to 15 represented by the letters A through F. See the following table.

Decimal Value	Hex Code
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
A (10)	1010
B (11)	1011
C (12)	1100
D (13)	1101
E (14)	1110
F (15)	1111

As an example to convert the binary number 101000110101100 to hex, you divide the word into 4-bit groups starting on the right and then replacing each with the hex codes. In this case, the hex code is A35C.

Parallel and Serial Data

It is frequently necessary for digital devices to communicate. Someone using a computer may have to send data to a printer. Or two people using personal computers may have to communicate over a local area network (LAN). To accomplish either of these objectives, one must transmit binary data from one circuit to another. This is done in one of two ways: parallel transmission or serial transmission.

Parallel Data

When the parallel method is used, all bits of a binary word or number are transmitted simultaneously. Fig. 5.4 shows an 8-bit word being transferred from logic circuit 1 to logic circuit 2.

A *bus* is a set of parallel data lines over which digital data is transferred. A data bus can have any number of data lines as required by the application. However, the main characteristic of a bus is parallel data transfer. In physical form, a bus is usually implemented on a connector, with lines of copper on a printed circuit board or with a ribbon cable with one wire per bit.

Because all bits are transmitted at the same time over a parallel bus, data movement is extremely fast. The main benefit of parallel data transmission is its high speed. With high-speed logic circuits, a binary word can be transferred from one point to another in as little as several nanoseconds. Parallel data transmission over buses in computers takes place at rates up to several hundred megahertz. It is not uncommon to see a rate of 100 million bits per second (Mbps) on a personal computer data bus. On long buses, data rates are slower because the stray inductance and capacitance of the cable typically distorts the data and slows the transmission speed.

Although parallel transmission is fast, it is expensive, because there must be circuitry for each bit on both the sending and receiving ends. There must be one wire per bit in a cable plus a separate ground wire. This increases the complexity and thereby the cost of the circuitry.

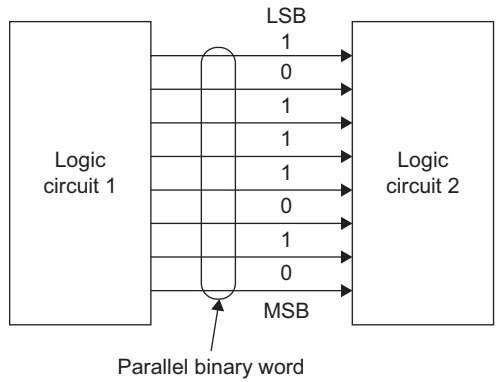


FIGURE 5.4 Parallel binary data transfer over bus.

Serial Data

The other method of moving binary data from one point to another is serial transmission. In the serial method, the bits of a word are transmitted one at a time, or sequentially. Fig. 5.5 shows the waveform of an 8-bit serial binary word. This is the voltage that you would monitor at the single output of the circuit generating the word. It is the waveform that an oscilloscope would display. Each bit occurs for a fixed time interval such as 1.5 ms. Thus, it takes $1.5 \times 8 = 12$ ms to transmit an 8-bit word.

The speed of data transmission is measured in bits per second (bps). That figure can be calculated from the expression:

$$\text{bps} = \frac{1}{t}$$

Here, t is the time for 1 bit. In Fig. 5.5, 1 bit takes 1.5 µs. The speed of the data, then, is

$$\text{bps} = 1 \div \left(1.5 \times 10^{-6}\right) = 666,666.7 \text{ bps or } 666.7 \text{ kbps}$$

If you know the speed in bps, you can calculate the bit time (t) by rearranging the formula:

$$T = \frac{1}{\text{bps}}$$

Assume a data rate of 14,400 bps. The bit time is 69.4 µs.

As seen in Fig. 5.5, the MSB is transmitted first. Depending on the system used, however, the LSB can be sent first. In any case, the speed of transmission depends on the number of bits in the word and the duration of each bit. It is this longer transmission time that is the primary disadvantage of the serial method. However, although serial transmission is slower than parallel transmission, it is perfectly suitable for many applications. Common data rates are in excess of millions of bits per second. Data rates of up to 100 Gbps are common.

The main benefits of the serial method are its simplicity and low cost. Only a single line rather than multiple lines is needed to interconnect the

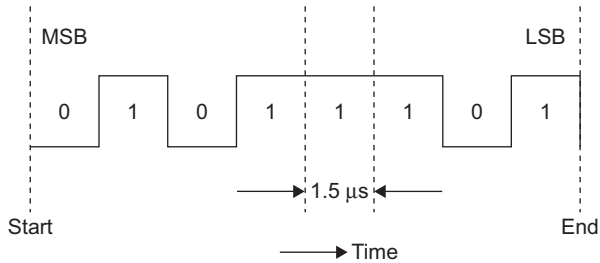


FIGURE 5.5 Serial data transfer where 1 bit occurs after another in time.

equipment. In addition, only one set of sending and receiving circuits is needed. All data transmissions by copper cable or fiber optical cable exceeding about 100 Mbps are made by the serial method. All wireless data transmissions are serial.

DIGITAL LOGIC ELEMENTS

Digital logic elements are the basic circuits that are used to process the binary data. The logic element has one or more binary data inputs to be processed. The logic element processes or manipulates the binary input signals in a fixed way and generates an appropriate output signal. The output is a function of the binary states of the inputs and the unique processing capability of the logic element. The logic element "looks" at the binary input signals and then makes a decision and generates an appropriate output. There are five elementary logic circuits: inverter or NOT, AND, OR, NAND, and NOR. These functions are performed by logic elements known as inverters and gates.

You need not be concerned with the inner workings of these logic elements. Instead, your primary concern is with the basic logic functions. Needless to say, the gates and inverters are inside every microcomputer and digital integrated circuit (IC).

Inverter

The inverter has a single input and a single output. The logic function performed by an inverter is *inversion*. The output of the inverter is simply the inverse, or opposite, of the input. Because binary signals can assume only one of two different states, either 0 or 1, the inverter generates a 0 when the input is a 1 and a 1 when the input is a 0.

Two common symbols used to represent an inverter are shown in Fig. 5.6. The input and output are given names, which are usually letters of the alphabet.

There are a variety of ways to express the operation of various logic functions. One way is to use Boolean algebraic expressions. A Boolean expression

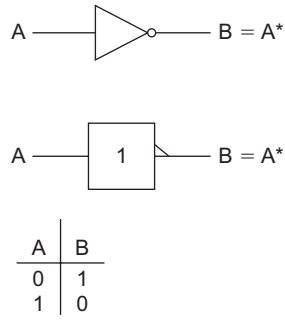


FIGURE 5.6 Logic symbols for inverter and truth table.

is a simple mathematical or algebraic formula that expresses the output in terms of the input. The Boolean expression for the inverter is:

$$B = A^*$$

This equation is read, "B equals not A." The asterisk means NOT or inversion. What this expression is telling you is that if the input is A, the output, B, is not A.

Another method of expressing the function of a logic element is a truth table. This is simply a table listing all possible combinations of the inputs and outputs of a logic element. Fig. 5.6 also shows the truth table for an inverter. There are only two possible inputs, 0 and 1, and the corresponding outputs. A truth table completely defines the operation of a logic element.

AND Gate

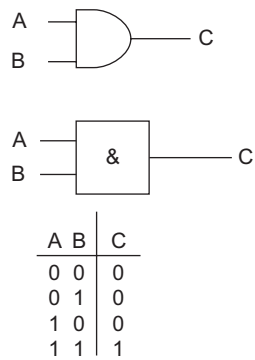
A gate is a circuit that has two or more inputs and a single output. The gate generates a binary output that is a function of the states of the inputs and the nature of the gate itself.

The type of gate determines how the binary inputs are processed. The two basic logic gates are the AND gate and the OR gate. An AND gate is a logic circuit that generates a binary 1 output if all of its inputs are binary 1s. Otherwise, the circuit generates a binary 0. All of the inputs have to be binary 1 for the AND gated to produce a binary 1 output. If any one of the inputs is a binary 0, the output is binary 0.

Fig. 5.7 shows the logic symbols used to represent an AND gate. Letters of the alphabet are used to represent inputs and outputs. There may be more than two inputs, but there is only one output.

As with the inverter, the output of the AND gate can be expressed in terms of the inputs with a Boolean expression. The Boolean expression for an AND gate is:

$$C = AB$$



A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

FIGURE 5.7 Logic symbols for AND gate and truth table.

This equation is read, "C equals A and B." Parentheses also can be used to separate the inputs; for example, C = (A) (B).

The truth table for a simple two-input AND gate is also shown in Fig. 5.7. Note that the output C is a binary 1 when both inputs are binary 1s. At all other times, the output is binary 0. With two inputs, there are a total of four different input combinations ($2^2 = 4$). With three inputs, there are $2^3 = 8$ possible input combinations for an AND gate. These inputs are the binary numbers 000 through 111.

One of the most common applications of an AND gate in digital circuits is gating. Gating simply refers to the use of one binary signal to control another. A two-input AND gate is most often used as a control gate. One input signal is the control that either keeps the other input signal from passing through to the output or allows it to pass.

Fig. 5.8 shows the inputs and output of a typical control gate. Note that multiletter names called *mnemonics* are used instead of single letters to designate the input and output signals. The ENB or enable input represents the control signal. As long as the ENB input is a binary 0, the output is a binary 0. The gate is said to be inhibited because nothing more than a binary 0 output occurs.

When the ENB control input is a binary 1, the gate is enabled. At this time, the main input signal, CLK for clock, is allowed to pass through to the output BST. CLK is a periodic clock signal that switches repetitively between the binary 0 and the binary 1 levels at a fixed frequency. The output of the AND gate follows the CLK input as long as the ENB control input is a binary 1.

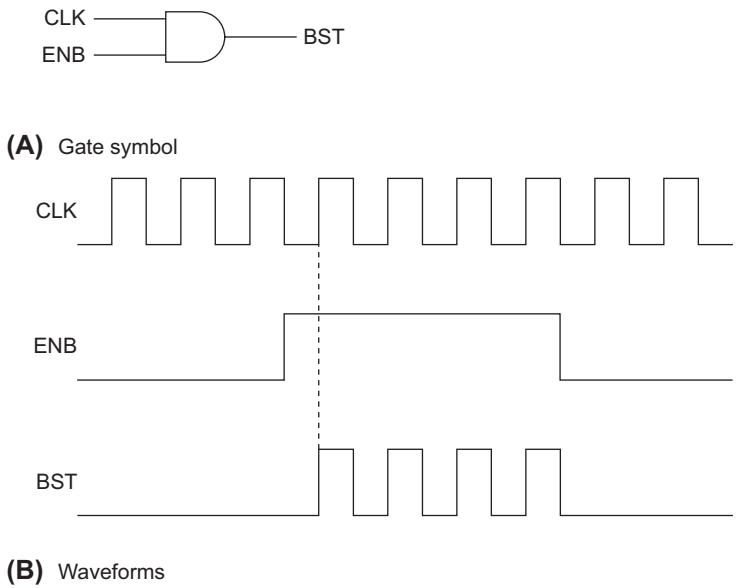
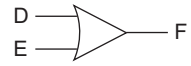
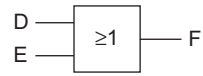


FIGURE 5.8 How AND gate is used to turn signal off or on. (A) The AND gate showing the input and output names. (B) The waveforms of the inputs and output.





D	E	F
0	0	0
0	1	1
1	0	1
1	1	1

FIGURE 5.9 Logic symbols for OR gate and truth table.

OR Gate

Another commonly used logic gate is the OR circuit. Like the AND gate, the OR gate has two or more inputs and a single output. The OR gate generates a binary 1 if any one or more of its inputs are binary 1. The only time the output of an OR gate is binary 0 is when all its inputs are binary 0.

The symbols used to represent an OR gate are shown in Fig. 5.9. Letters of the alphabet are used to designate the inputs and outputs. Using these designations, the Boolean output expression for the OR gate is:

$$D = E + F$$

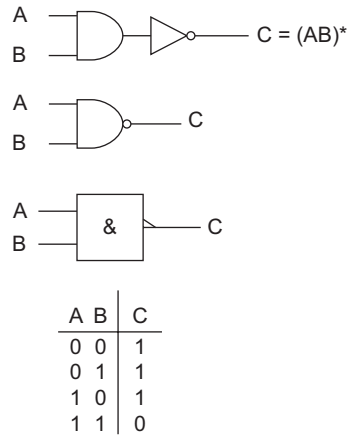
This equation is read, "D equals E or F." In this Boolean expression, the plus sign designates the OR function. In a Boolean logic expression, the plus sign does not mean addition. In Fig. 5.9, the mathematical symbol (greater than or equal to) is used to designate the OR logic function. The truth table for an OR gate further defines its operation. The output D is a binary 1 when input E or input F or both are a binary 1. Like an AND gate, an OR gate can have any number of inputs.

NAND and NOR Gates

The AND and OR logical functions are basic to all digital systems. Although these functions are implemented with AND and OR gates, a variation of these gates is even more widely used. These are NAND and NOR gates, which are a combination of either an AND gate or an OR gate and an inverter. These gates are more flexible in their application when they are used together.

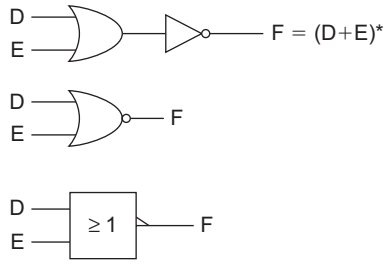
A NAND gate can be made with an AND gate followed by an inverter. Fig. 5.10 shows this circuit configuration. Note the two special symbols in Fig. 5.10 used to represent the logical NAND function. The truth table is also given.

A NAND gate can perform all of the gating and detection functions mentioned earlier for an AND gate. The only difference is that the output is inverted.



A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

FIGURE 5.10 Logic symbols for NAND gate and truth table.



D	E	F
0	0	1
0	1	0
1	0	0
1	1	0

FIGURE 5.11 Logic symbols for NOR gate and truth table.

The other widely used digital logic element is a NOR gate. A NOR gate is a combination of an OR gate followed by an inverter (see Fig. 5.11). The symbols used to represent the NOR logic function are also shown. The output of a NOR gate is simply the complement of the output of an OR gate, as shown by the truth table. An XOR actually is a 1-bit binary adder.

Exclusive OR Gate

A variation of the OR gate is the exclusive OR, usually designated XOR. Its symbols are given in Fig. 5.12. The truth table is also shown. Note that the circuit only produces a 1 output if the two inputs are opposite. The output is 0 if the two inputs are the same. An XOR gate is used to make an adder.

An inverted XOR or XNOR has the symbols and truth table shown in Fig. 5.12. It is useful as a 1-bit comparator since the output is 1 if both inputs are the same.

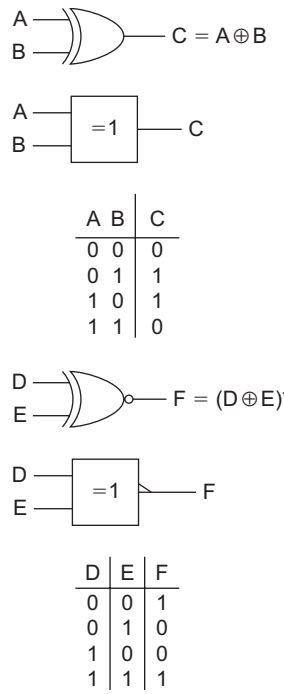


FIGURE 5.12 Logic symbols for XOR and XNOR gates and truth tables.

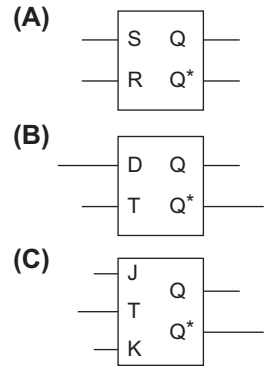


FIGURE 5.13 Logic symbols for flip-flops. (A) RS. (B) D type. (C) JK.

Flip-Flops

A flip-flop (FF) is another basic building block of electronics. It is essentially a circuit that stores 1 bit of data. The circuit has two states—set and reset. If the FF is storing a binary 1, it is set. If it is storing a binary 0, it is reset. Fig. 5.13A shows the basic block diagram of a reset–set (R–S) FF. The inputs are set (S) and reset (R). The two outputs Q and Q* are complementary. You apply an input to the appropriate input to set or reset the FF.

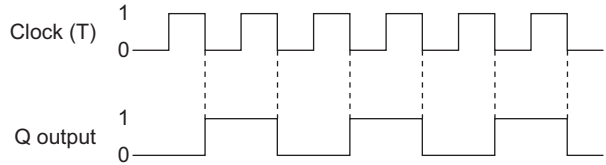


FIGURE 5.14 Toggling T input on JK flip-flop causes it to change states, producing frequency division by 2.

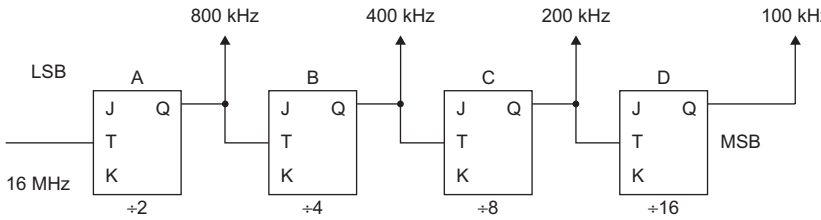


FIGURE 5.15 Cascading JK flip-flops produce higher-frequency division ratios, which is also a binary counter that counts from 0000 to 1111.

A D-type FF is shown in Fig. 5.13B. It has a D or data input and a clock (T) input. When the clock occurs, the FF is either set or reset depending on the value of the D input. The D FF is used to store 1 bit of data.

Another type of FF is the JK, shown in Fig. 5.13C. It has J and K inputs that correspond to S and R inputs, respectively. It also has a clock or T input that performs the set or reset operations. To store a binary 1, you make J = 1 and K = 0. When a clock input occurs, the FF is then set or reset.

The T input also causes the state of the FF to toggle or change state when a clock transition occurs (see Fig. 5.14). This feature is used to produce frequency division by 2 as shown. The output is a square wave half the frequency of the T input. Additional JK FFs can be cascaded to produce frequency division by the power of 2 or 2, 4, 8, 16, 32, 64, and so on, as shown in Fig. 5.15.

Storage Registers

A storage register is a place to store a binary word or number. It is made up of 1 FF per bit. An 8-bit register stores bytes and has 8 FFs. Fig. 5.16 shows a register with eight inputs and eight outputs. Most registers also have a clock input also called LOAD or STORE that determines when the input data is stored. Some also have a CLEAR or RESET input that puts all the FFs in the binary 0 state.

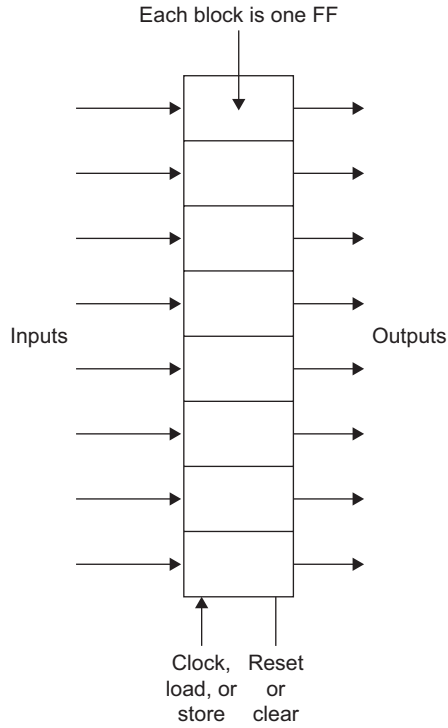


FIGURE 5.16 Storage register from one word consists of FFs. It also has clock/load and clear/reset inputs.

Shift Registers

A shift register (SR) is like a storage register, but the bits stored there may be shifted from one FF to the next as each clock pulse occurs. Fig. 5.17A shows how serial binary data is shifted into the SR for storage. As new data is shifted in, the existing data will be shifted out and sent to another circuit. Fig. 5.17B shows data being shifted out as binary 0s are shifted in.

SRs are often used for parallel-to-serial and serial-to-parallel conversions. A serial-to-parallel conversion is shown in Fig. 5.18A. The SR initially contains all binary 0s. Then serial data is shifted in, and the output is taken in parallel from the FF outputs. For parallel-to-serial conversion, a binary word is initially stored in the register. Then the word is shifted out as the clock pulses occur (see Fig. 5.18B).

Counters

As its name implies, a counter is a circuit that counts input pulses. Counters are made of multiple cascaded FFs, and they are sometimes accompanied by

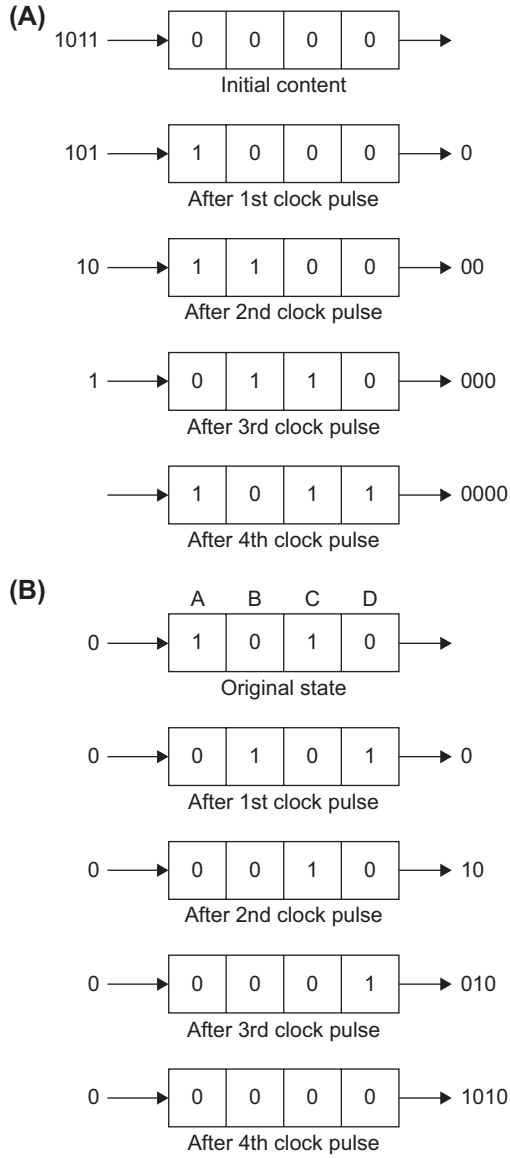


FIGURE 5.17 (A) Shifting serial data into shift register. (B) Shifting serial data out of shift register.

logic gates. As the input pulses occur, the binary number stored in the counter FFs tells how many pulses have occurred. The frequency divider shown in Fig. 5.15 is also a 4-bit counter. It can count from 0 (0000) to 15 (1111). If all FFs are initially reset to 0, then 10 pulses occur, and the FFs from A to D would be storing 0101 from left to right. The rightmost FF (D) is the MSB, so you read the counter as 1010 or the binary equivalent of decimal 10.

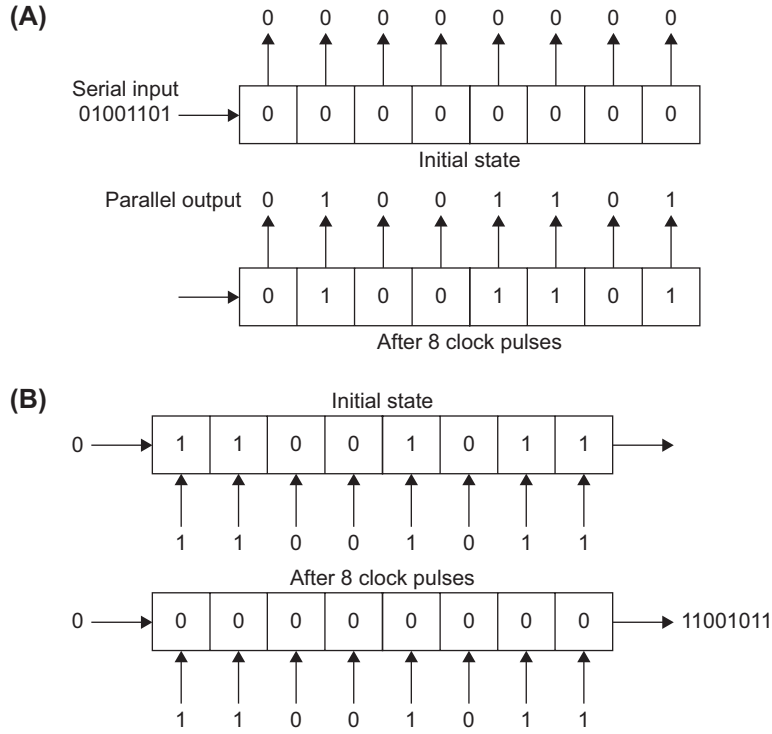


FIGURE 5.18 Shift registers used for (A) serial-to-parallel data conversion and (B) parallel-to-serial data conversion.

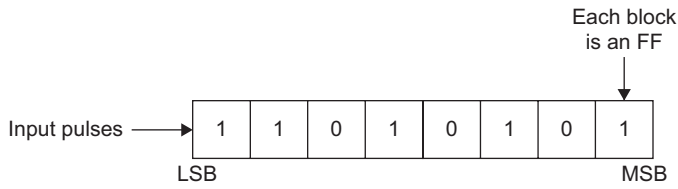


FIGURE 5.19 Counter storing binary value equal to number of input pulses that occurred.

Binary counters can store numbers up to $2^N - 1$, where N is the number of FFs. For example, an 8-bit counter would count from 00000000 to 11111111 or $2^8 - 1 = 256 - 1 = 255$.

Fig. 5.19 shows a counter where 178 pulses have occurred, so the counter stores the number 10101011 that is the binary equivalent of 179.

Another popular form of counter is the BCD version that counts from 0000 to 1001 or 0 through 9. BCD counters are used to keep track of decimal quantities in binary form. BCD counters can serve as frequency dividers as well. Each divides by 10.

COMMON LOGIC CIRCUITS

There are several types of logic circuits that occur again and again in digital equipment. The counters and registers just described are good examples. A few others that you may encounter are described in this section. Remember that these circuits can be made from individual gates and FFs in IC form. You can also buy them in IC form already wired for their specific function. But mostly these circuits appear as a collection of circuits inside some larger IC.

Multiplexer

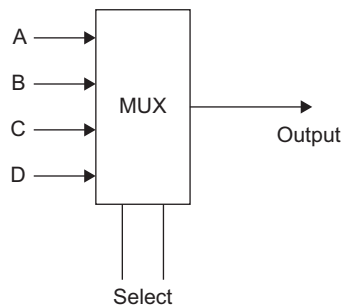
A multiplexer or mux or mpx is a circuit with two or more inputs and one output (see Fig. 5.20). Here there are four inputs and one output. Two other inputs are used to select one of the inputs to appear as the output. The four selected inputs are 00, 01, 10, and 11. In the figure, note which input is routed to the output with each input select code. Multiplexers can have as many inputs as needed.

Demultiplexer

A demultiplexer or demux is the opposite of a mux. It has one input and multiple outputs. Like the mux, select inputs specify which of the output lines the input is connected to.

Decoder

A decoder is a circuit that can detect a specific binary code. In its simplest form, it is just an AND gate, as shown in Fig. 5.21A. If the input 0110 appears at the inputs, the AND gate will have all its inputs at binary 1, so the output will



Select	Input at output
00	A
01	B
10	C
11	D

FIGURE 5.20 Digital multiplexer (mux) that selects one of four inputs to appear at the single output.

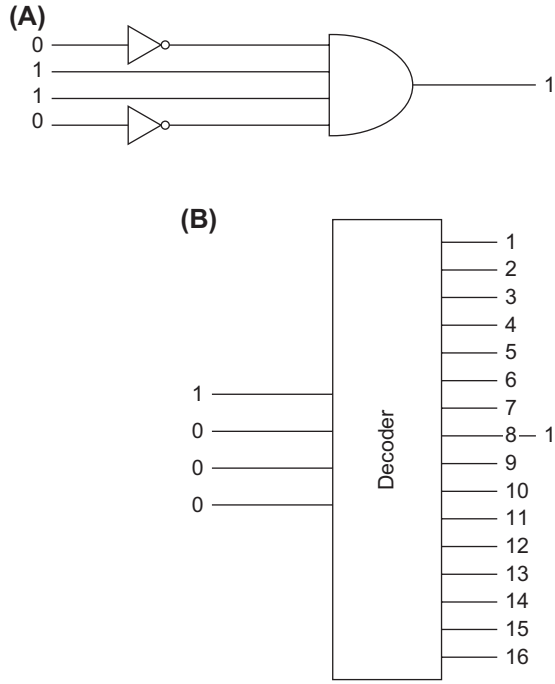


FIGURE 5.21 Decoders. (A) 1-AND gate decoder that identifies input 0110. (B) 4-to-16 decoder that identifies 1 of 16 different 4-bit input values.

be binary 1 indicating that it is detecting the desired input. For any other 4-bit input, the output will be binary 0.

Decoders can also be made to detect all states of a given binary input. For example, a 4-bit decoder like that in Fig. 5.21B looks at the 4-bit inputs and decodes all states from 0000 to 1111. If the input is 1000, the 8 output is binary 1, and all other outputs are 0.

Comparators

A comparator takes two binary words as inputs and compares them. If the two inputs are equal, a binary 1 output occurs. Otherwise, if the two inputs are different, the output is 0. Some comparators have outputs that can tell if one input is larger than or smaller than the other.

Arithmetic Circuits

Digital logic does a good job of basic arithmetic functions such as add and subtract. The basic computing element is called an arithmetic logic unit (ALU). It does binary addition and subtraction. It can also perform basic logic operations such as AND, OR, or XOR on two binary input words. Circuits for multiplication and division are more complex, but are common in digital computers.

DIGITAL MEMORIES

Digital memories are semiconductor circuits that store binary data. You have probably heard of the terms RAM and ROM as they apply to personal computers. These are the two main types of memory, random access memory (RAM) and read-only memory (ROM).

Random Access Memory

The RAM is one in which you can access hundreds, thousands, or millions of binary storage locations. You can store one binary number or word in each location or read the data out of the location. Each location is referred to by a unique binary number called the address. You send the memory an address and activate the selected location. Then you can read data from the location or write data into that location. RAMs therefore are what we call read-write memories.

Fig. 5.22 shows the concept of a RAM. It has eight locations for 4-bit words. To address eight locations you need a 3-bit address ($2^3 = 8$). When you apply the address to the address decoder, the decoder activates the desired location. In the figure you see that the binary number 1001 stored in location 011 is being accessed and read out.

Most memories are large today. We talk about megabytes (MB) or millions of bytes of data or gigabytes (GB) or billions of bytes of data in a modern PC. Embedded controllers will have fewer locations, usually in the thousands of bytes (KB) or perhaps more in the larger systems. Storage word sizes are usually 8 (bytes), 16, 32, or 64 bits.

There are two ways to make a RAM. The first way is just to build one FF for each bit to be stored. The basic set–reset FF described earlier is the basic

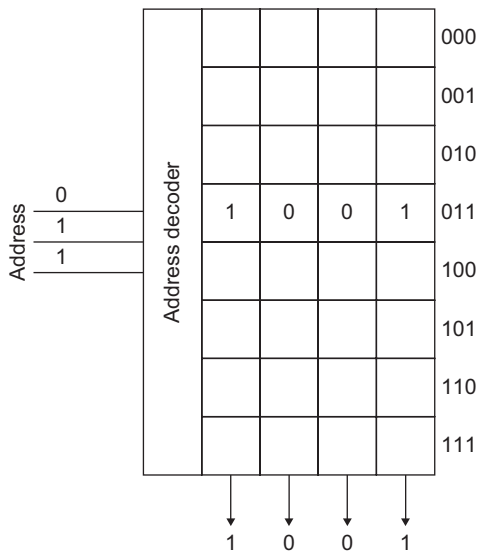


FIGURE 5.22 Basic concept for random access memory (RAM). Address selects one of eight storage locations. Then data may be read from that location or data stored in it.

storage circuit (see Fig. 5.23A). Memories using this type of circuit are called static RAM or SRAM. They are called static because once you store the bit in the FF, it stays there as long as power is applied to the circuit.

The other form of RAM is called *dynamic RAM* or DRAM. The basic storage circuit is a capacitor as shown in Fig. 5.23B. If you charge the capacitor, it is storing a binary 1. If the capacitor is discharged, a binary 0 is being stored. A MOSFET is used as a switch to access the capacitor. If the MOSFET is turned on by an input address on the gate, it connects the capacitor to the data line, where it may be read out or where a new bit may be stored. When the MOSFET is turned off, the capacitor is isolated and just stores the bit.

The reason why the term *dynamic* is used for this type of RAM is that the charge on the capacitor will leak off very quickly. The capacitor is very small, and millions of them are made on a tiny chip of silicon. For this reason, the capacitor has to be recharged every so often so that the data is retained. This is called a refresh operation, and it usually occurs every 2 ms or so.

Comparing SRAM and DRAM, you should know that SRAM is the faster of the two in that you can store data or read data out faster than you can with a DRAM. The downside is that the SRAM is more complex and takes up more space on the chip, and thus costs more. The DRAM is slower but not much. Its advantage is that you can put more storage cells on a chip, making them cheaper. The need to refresh is a downside but easy to live with, as all the refresh circuitry is on the chip, and the process is transparent to the user.

Just keep in mind a key fact. RAM is fast and reliable, but it loses all data if the DC power to the memory circuit is removed. All data is erased. RAMs are therefore said to be volatile.

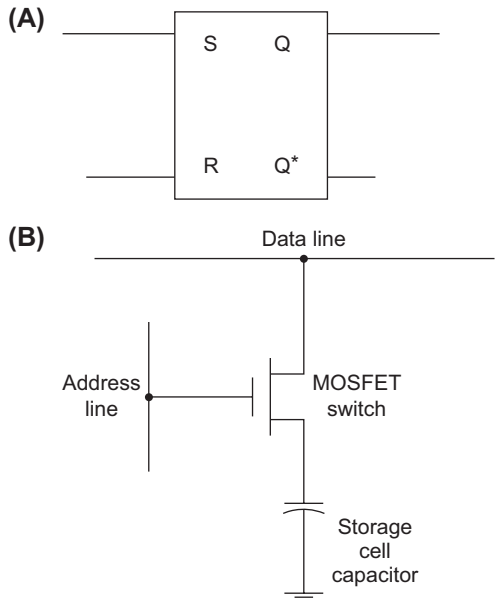


FIGURE 5.23 RAM storage cells. (A) RS FF for SRAM. (B) Capacitor cell for DRAM.

A newer memory type is the ferroelectric RAM or FRAM. Its basic structure is similar to that of the capacitive DRAM cell of Fig. 5.23B. The difference is that the dielectric material in the capacitor has magnetic capabilities. When data is written into or data is extracted from the cell, electric field state is stored magnetically. That means that the cell remembers its state after an operation even if power is removed. This makes FRAM nonvolatile like ROM. FRAM is fast and uses very low power. This type of memory is used in some newer microcontrollers.

Read-Only Memory

ROMs are nonvolatile memories. Once you store data in them, they retain the data when power is removed. In some ROMs, you can change the data stored there. Incidentally, all ROMs are random access in that you can go to any desired location to read or maybe write data.

There are several categories of ROM. The older types are called masked ROM, where the mask refers to the actual wiring of the ROM to permanently fix the data in the circuitry when it is made. The storage cells are essentially a MOSFET matrix where each MOSFET is permanently turned on or off to store 1 or 0. No changes are possible. Later a programmable ROM or PROM was developed. It used a special MOSFET that could be programmed on or off. You could then erase the programming by shining ultraviolet (UV) light on the chip for a short time. Then the PROM could be reprogrammed. These are no longer used.

Most ROMs today are what we call electrically erasable programmable ROMs or EEPROMs or E^2PROMs. The storage element is a MOSFET that you turn off or on with a programmable voltage (see Fig. 5.24). The MOSFET retains that state until it is electrically changed.

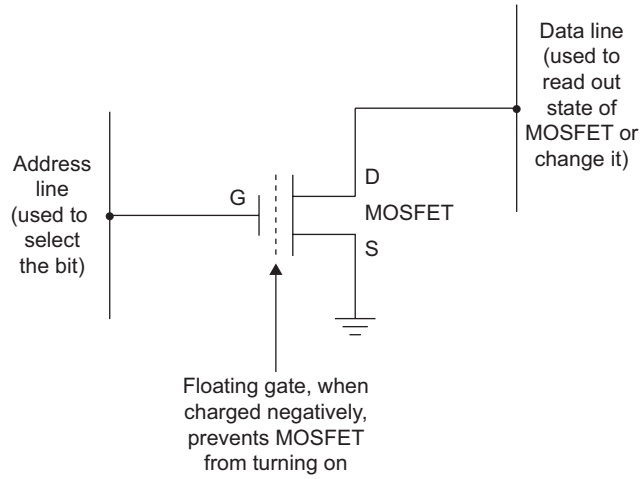


FIGURE 5.24 Storage cell used in EEPROM and flash memories is MOSFET with a special floating gate that keeps transistor off or on.

The main problem with EEPROMs is that they are slow to erase and reprogram. But today we have a special version of EEPROMs called flash memories. These are also EEPROMs, but they actually are almost as fast as RAMs for reading and writing data. Yet they are nonvolatile.

You will hear of two types of flash memory—NOR and NAND. NOR flash is used to store programs for microcontrollers. It can only be erased on large block sizes and not individual cells. NAND flash is faster, and you can erase individual memory locations. The NAND flash is gradually replacing the NOR flash in many applications.

Flash memory has become so popular that it is used in almost every electronic product today. MP3 players and iPods store music in flash memory. Cell phones store phone numbers, digital cameras store photos, and in embedded controllers, the flash usually stores the program that tells the processor what to do. And, let us not forget the flash drive or "thumb" drive as it is called. These devices with a USB connector can store many gigabytes of data and are very inexpensive. Flash memory is also used to make solid-state drives (SSDs) that are the equivalent of the hard disk drives used in PCs and laptops. They are still expensive, but as prices continue to decline, you will see more SSDs replacing conventional mechanical/magnetic hard drives.

PROGRAMMABLE LOGIC DEVICES

There are two ways that digital devices are built today. The most common is to use an embedded controller or microcomputer. This is a single-chip computer that you can program to do whatever digital function you want. Most electronic products have at least one embedded controller at the heart of their design.

In some cases, the embedded controller is not fast enough to do the job. One way to make the circuitry is to use individual logic circuits such as gates, FFs, counters, and so on. That is the way it used to be done. Now, if you need fast custom digital logic, you build the circuit with a programmable logic device (PLD). A PLD is an IC that contains a mix of gates, FFs, and other circuits that can be programmed to implement any digital function. The programming is usually done on a computer, and a file is created. The file is then downloaded to the PLD, where it is stored in a RAM or ROM. The file in the memory determines how the unique circuit is formed.

There are three basic types of PLDs: simple PLDs (SPLDs), complex PLDs, and field programmable gate arrays (FPGAs). The SPLDs are small devices for simpler digital circuits. The most common types are called programmable array logic (PAL), programmable logic arrays (PLAs), and generic array logic (GAL). PROMs are also used as SPLDs. For example, the address input to a ROM is some binary number or a collection of binary inputs. These form an address to locate a specific binary word stored in that location. When that particular selection of input bits occurs, it forms the address that identifies the memory location where the desired set of output responses is stored. This form of SPLD is also called a lookup table or LUT.

The other SPLDs are essentially a set of AND and OR gates that can be programmed. They all take the form shown in Fig. 5.25. You can select which inputs go to the AND gates, and/or select which AND outputs go to which OR gate inputs. A PROM has the AND array fixed, and you can program the OR gates. A PAL is an SPLD in which you can program the AND inputs, but the OR connections are fixed. A PLA is a PLD that lets you program both the AND

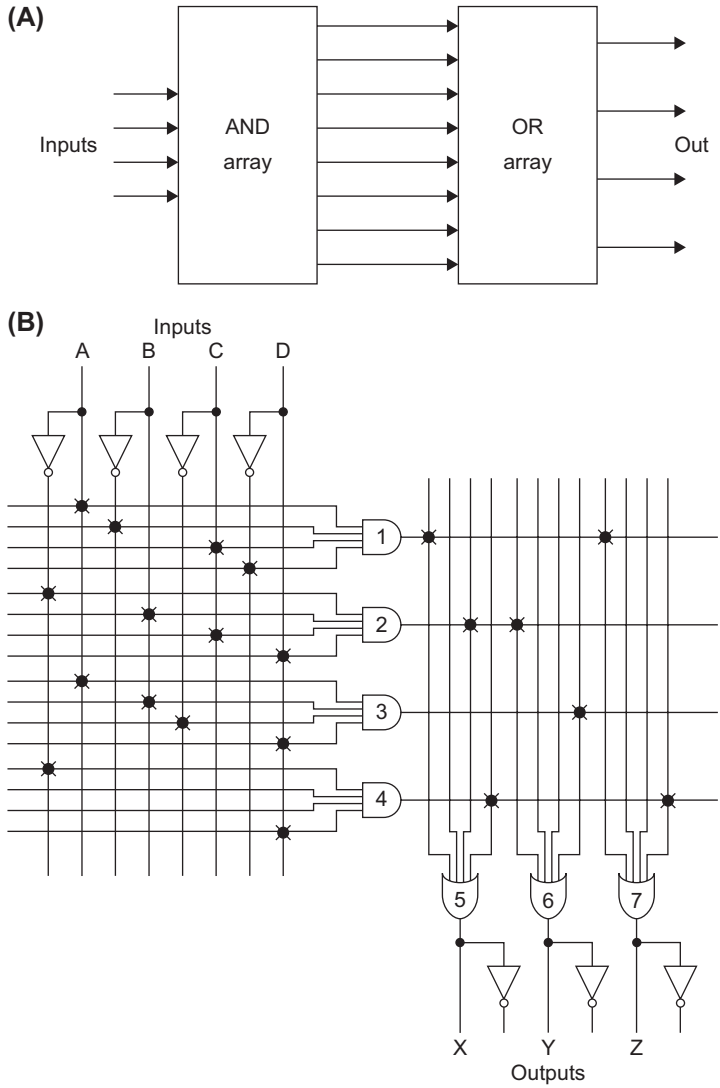


FIGURE 5.25 PLD concept. (A) Block concept of programmable AND and OR gate arrays. (B) Simple circuit of PLD showing programming by dots on AND and OR gate arrays.

inputs and the OR connections. In both PLAs and PALs, the programming is usually permanent.

A GAL is a variation of the PAL with its AND inputs programmable. The difference is that the programming can be changed. The program you develop is actually stored in flash memory. The flash memory cells send the programming bits to the various AND and OR gates telling them what logic to implement. You can then erase it and reprogram if you want or need to. GALs also have one or more FFs associated with the logic gates, so you can store bits or actually build counters and registers by programming.

CPLDs are complex PLDs similar to SPLDs, only larger. They contain more gates and FFs so that very large logic projects can be built on a single chip. A typical CPLD is really just a large collection of PALs or GALs that can be individually programmed and then connected together with a large interconnect matrix. Input/output (I/O) circuits also provide inversion if needed or extra power to drive external circuits. Again, flash memory is used to store the programming.

The largest and most flexible PLD is the field programmable logic array or FPGA. It has become the most popular and common way to implement digital equipment other than a microcontroller. FPGAs are large chips that contain thousands of logic circuits. The largest devices have millions of gates and other circuits. Most FPGAs are programmed by storing a bit pattern in the SRAM cells inside. These cells tell the logic circuits what configuration to take and what functions to perform. If you turn the power off, the programming goes away, and all you have is a dumb FPGA with no logic interconnections or functions. When you power up an FPGA, the desired program, usually from a flash memory, or a computer loads the RAM cells with the program, thereby enabling the FPGA to perform its desired function.

The logic inside an FPGA is essentially thousands of LUTs that can be individually programmed. Each LUT has its own program memory block as well as one or more FFs and I/O circuits. The LUTs may also be interconnected to one another by programming. With this arrangement virtually any digital logic operation can be programmed. Some of the newer FPGAs also include microprocessor cores and common I/O interfaces.

There are about a half-dozen companies that make PLDs. The two oldest and largest are Xilinx and Altera (Intel). Both have extensive lines of CPLDs and FPGAs.

DATA CONVERSION

The term *data conversion* refers to the translation of analog signals into digital form and vice versa. While it used to be an all-analog electronics world, today it is virtually all digital. We still have analog signals such as voice, video, radio waves, and sensor voltages, but mostly we process, store, and transmit data by digital means. For that reason, circuits that perform these conversions are critical to virtually all electronic applications. All cell phone voice is digital, all

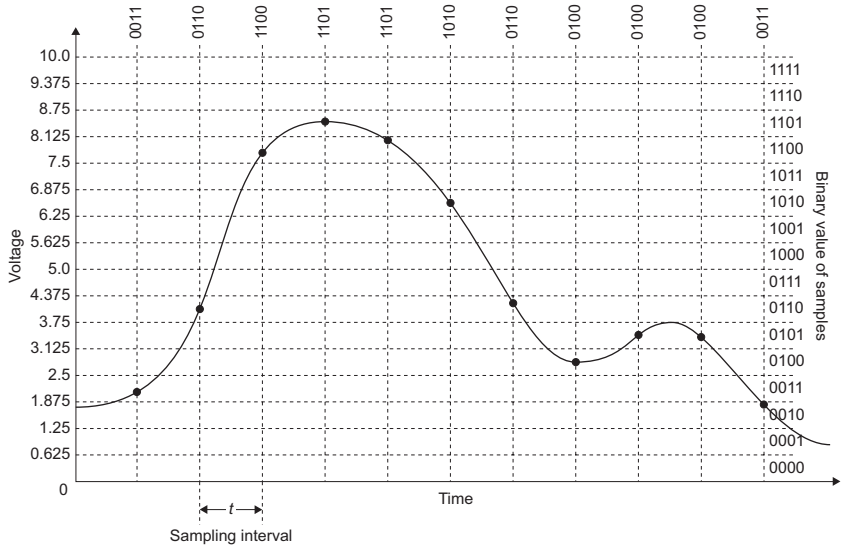


FIGURE 5.26 Analog-to-digital conversion is performed by sampling analog signal at equal intervals and generating proportional binary value.

modern TV is digital, and sensor outputs are captured and processed in digital form. It is difficult to name a product today that does not use some form of data conversion.

Analog-to-Digital Conversion

The process of converting an analog signal into a digital one is called analog-to-digital conversion, and it is performed by an analog-to-digital converter (ADC). The process, also referred to as sampling, is illustrated in Fig. 5.26. The ADC looks at the analog input and periodically takes a sample of the voltage at that instant, captures it, and then converts it into a proportional binary number. We say that we are digitizing the signal. The sample points are shown by the dots on the analog curve. The binary value of the sample is shown to the right of the curve. The conversion process actually results in a sequence of binary numbers that represent the analog waveform. These values are usually stored in a RAM or transmitted to other circuits as shown in Fig. 5.27. Note the symbol for an ADC.

Digital-to-Analog Conversion

To recover the original signal, we put the data sequence previously captured by the ADC into a digital-to-analog-converter (DAC) (see Fig. 5.28). The output is a version of the analog signal. The DAC output is not a perfect reproduction, but just an approximation. This is shown in more detail in Fig. 5.29. Each

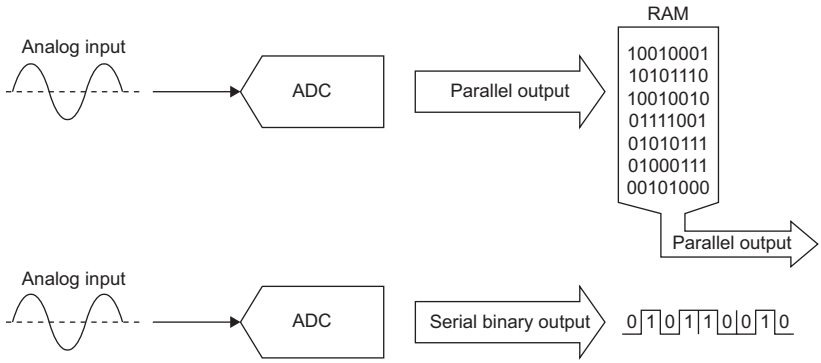


FIGURE 5.27 Symbol for ADC with both parallel and serial output examples.

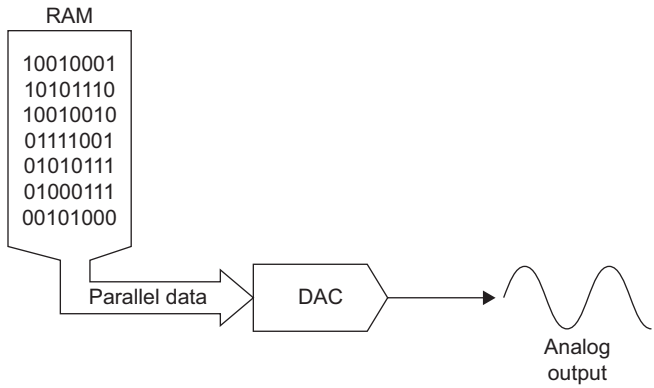


FIGURE 5.28 Converting binary data back into analog signal with DAC.

binary input results in a constant voltage output from the DAC during the sample period. The result is a stepped approximation to the original signal. The rate at which the binary data is sent to the DAC must be the same as the sampling interval to recover the original frequency information in the signal.

Resolution and Sampling Interval

The key to good data conversion is to use greater resolution and faster sampling rates. Resolution refers to the number of bits used in the data conversion. In Fig. 5.27, only 4 bits are used, so the resolution is poor. The voltage range is only divided into 16 intervals, meaning that amplitude variations at less than 0.625 V are missed. This problem can be corrected by using more bits. ADCs are available in many bit sizes. The most common are 8, 10, and 12 bits, but 14 and 16 bits are available. Some methods of ADC produce resolutions of 20–26 bits. The result is a finer conversion of amplitude detail. As an example, if the 0- to 10-V range in Fig. 5.27 was sampled with a 12-bit ADC, the individual smallest

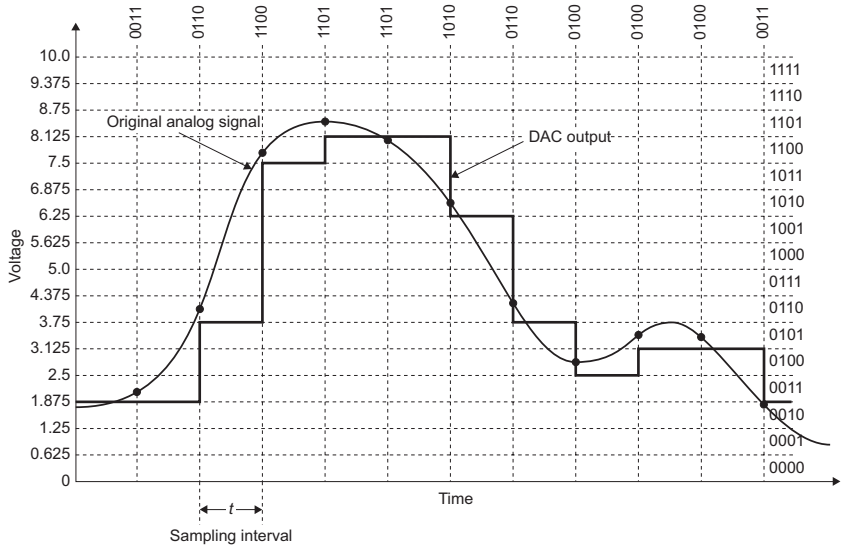


FIGURE 5.29 DAC output is stepped approximation to original analog signal.

voltage increment that can be detected is $10/2^{12} = 10/4096 = 2.44\,\text{mV}$ instead of the 0.625V in the figure.

Another critical specification is sampling rate. To retain all the frequency detail in a signal, the sampling rate must be at least twice the highest frequency in the signal. This is called the Nyquist criterion. For example, when digitizing music with a frequency range of 20 Hz–20 kHz, the sampling rate must be at least double the 20-kHz frequency. In most systems, a rate of 44.1 or 48 kHz is used.

ADCs with sampling rates to tens of gigahertz are commonly available, meaning that even radio signals can be digitized.

Direct Digital Synthesis

In Chapter 4 you learned how a phase-locked loop (PLL) synthesizer works to generate a variable frequency output. A newer way to generate an output signal is direct digital synthesis (DDS). It uses the sampling principles described here along with a DAC to produce a variable frequency output of any desired waveshape.

Fig. 5.30 shows a basic DDS. Stored in the memory are samples of a sine wave as they may have been produced by an ADC. A memory address register sends sequential addresses to the memory, and the samples are read out and sent to a DAC where a stepped approximation of the sine wave is produced. A low-pass filter (LPF) smoothes the output into a near perfect sine wave.

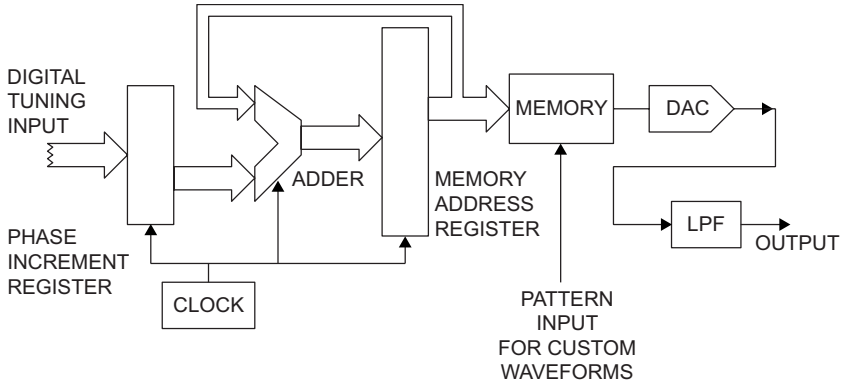


FIGURE 5.30 A generic block diagram of a direct digital synthesizer (DDS).

Changing frequency is a bit tricky since the clock is a fixed frequency. To change frequency, the circuit selects the specific samples to be used for the output. This is done by adding a phase increment constant value to the memory address register value in an adder. The effect is to use more or less of the samples in the output. Increasing the phase increment value increases the output frequency and vice versa.

The DDS has become quite popular because it is available as a completely easy-to-use IC. Furthermore, almost any unique waveform pattern can be stored in the memory making the DDS an arbitrary waveform generator (AWG). DDS chips are available to produce outputs up to about 100 MHz.

Project 5.1

Building a 5 V Power Supply

The digital projects to follow use CMOS logic circuits that operate from +5 V. If you apply more than 5 V, you will destroy the IC. Any of the following power sources is suitable:

- the power supply kit you may have built in Project 4.1 set to 5 V;
- a regulated AC to DC 5 V wall adapter;
- the power supply you may have built in Project 4.7 (Fig. 4.33);
- the 6 or 9 V battery supply plus the 7805 regulator circuit in Fig. 4.33.

Project 5.2

Examining a NAND Gate

A NAND gate is a logic gate that implements the NOT AND function (Fig. 5.10). In this project you will demonstrate the operation of a NAND gate and a common application.

Continued

Project 5.2—cont'd

The IC you will use is the 74HC00, a quad two-input NAND. Four NAND gates in a 14-pin dual inline package (DIP). Fig. 5.31 shows the logic diagram and pin connections. Do the following:

- Plug the 74HC00 into your breadboard.
- Connect pin 14 to +5 V and pin 7 to ground or minus.
- Connect two short #22 wires into pins 1 and 2. These are the inputs. You will connect the wires to +5 V for a binary 1 and to ground for binary 0.
- Connect the 330-Ω resistor and LED as shown in the figure.
- Apply power to the circuit.
- Apply the inputs shown in the truth table of Fig. 5.31, and for each pair on inputs, note the output and record a 0 or 1 in the truth table. Your truth table should be like that in Fig. 5.10.

One common application of the NAND gate is to gate another signal. That is the circuit serves as an open or shut gate. Gating a clock signal is one widely used case. You will use the 555 timer circuit you built earlier as the clock. Do this:

- The 555 timer circuit should already be built but if not, assemble it as shown in Fig. 5.32. Use 5 V for the supply.
- Connect the 555 timer output from pin 3 to pin 1 of the NAND gate. The wire input to pin 2 of the gate is the enable or disable signal.
- Connect the wire from pin 2 to ground or binary 0. Does the LED flash?
- Now connect the wire from pin 2 to +5 V or binary 1. Does the LED flash? It should indicate that the gate is allowing the signal through. The voltage on pin 2 is the enable or gating signal.
- Turn off the power.

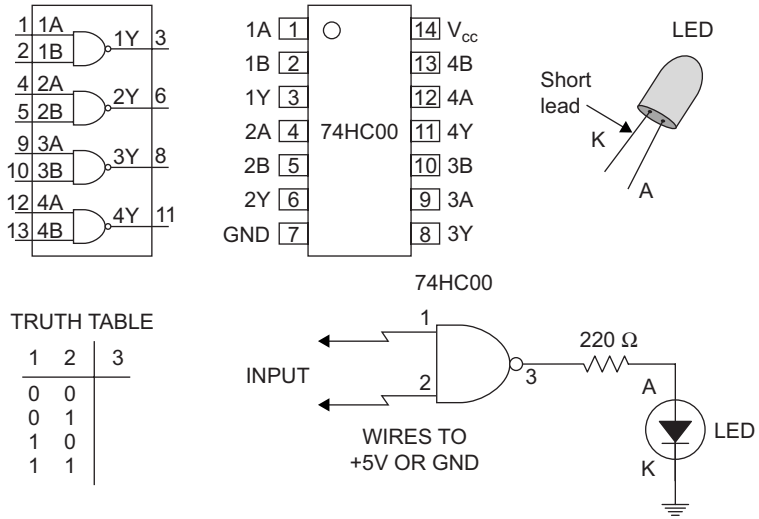


FIGURE 5.31 Pin out details of the 74HC00 quad NAND logic IC, a NAND test circuit with LED output, and a truth table.

Project 5.2—cont'd

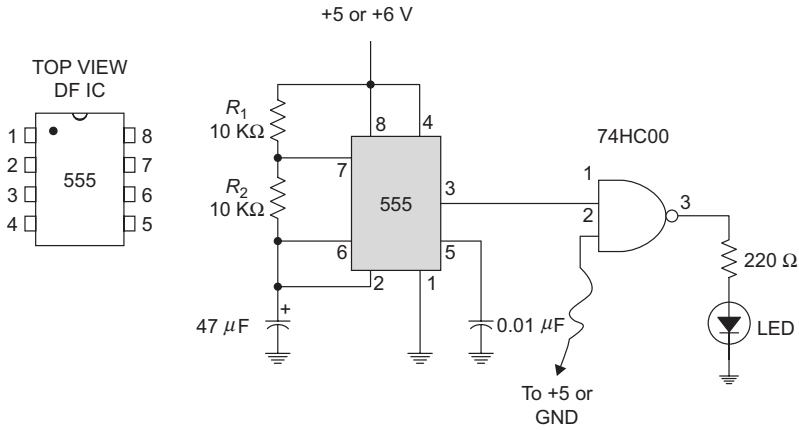


FIGURE 5.32 The output of a 555 timer is the input to a NAND gate.

Project 5.3

Demonstrating a Binary Counter

A binary counter is made up of FFs connected in a sequential arrangement. When an input is applied to the counter, it will toggle the FFs in a binary manner. The counter actually counts the number of input pulses and stores a binary value equal to the number of pulses received. As an example, a 4-bit counter counts from zero 0000 binary to 15 or 1111 binary. If the counter is initially reset or set to 0000 and 6 input pulses occur, the binary number stored in the counter will be 0110 or decimal 6. The binary state of each FF can be observed at each FF output.

The binary counter is also a frequency divider. Since each FF divides its input frequency by 2, an input of 50 kHz will produce a 25 kHz output. Cascading FF causes each FF to divide by 2. With a 4-bit binary counter a 50 kHz input will be divided down by a factor of 2^4 or 16–3.125 kHz observed at the fourth FF output.

In this project you will build a binary counter and observe its outputs as it counts. You will also demonstrate the counter as a frequency divider by looking at the FF outputs on an oscilloscope.

- Construct the circuit shown in Fig. 5.33. The 555 timer circuit of Fig. 5.32 that should still be working will be used as the clock signal to drive the counter.
- The counter is a 74HC161 4-bit counter IC. Its four outputs operate the four LED outputs. Be sure to connect pin 16 to +5 V and pin 8 to ground. Pins 1, 7, 9, and 10 are not used but need to be at +5 V and are connected by the 1k-Ω resistors. Double check the wiring of the circuit before you apply power.

Continued

Project 5.3—cont'd

- Apply 5 V. You should immediately see the LEDs flashing. The clock frequency is about 1 Hz. Observe for a while until you can identify the binary code sequence. It should correspond to the binary sequence shown in Box Hexadecimal Notation. Note in Fig. 5.33 which LED represents the LSB and the MSB. The pattern will repeat after each 16 input pulses.
- Turn off the power.
- Replace the 47-μF capacitor in the 555 circuit to a 0.01 μF ceramic. This will increase the clock frequency to about 4.8 kHz with a period of just over 200 μs.
- Turn on the power. The LEDs are flashing too fast for you to follow so they all just glow dimly.
- Use your oscilloscope to view the FF outputs. If you have a dual trace scope, you can look at two waveforms at the same time. Look at the 555 timer output at pin 3 or at pin 2 of the 74HC161. Then look at each FF output at pins 14, 13, 12, and 11 and note how each output frequency is half the previous output. The output at the fourth FF (pin 11) should be about 300 Hz with a period of about 3.33 ms.
- Turn off the power.

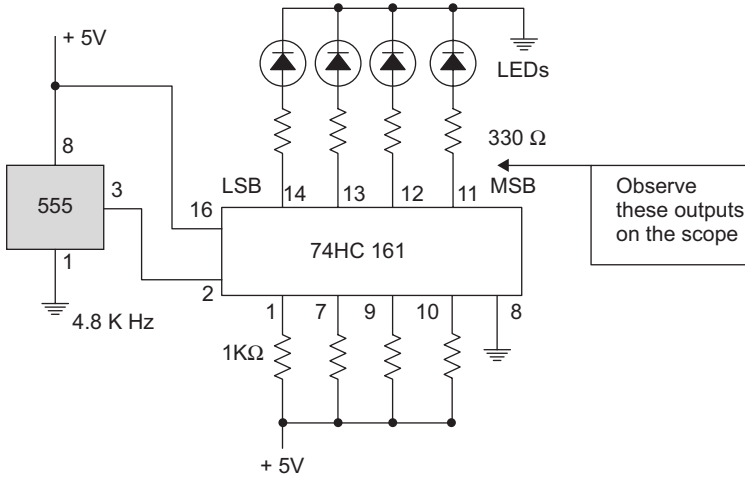


FIGURE 5.33 A 74HC161 IC binary counter clocked by a 555 timer to demonstrate the binary count sequence on LEDs.

Chapter 6

How Microcomputers Work

The Brains of Every Electronic Product Today

In this Chapter:

- Microprocessors, microcomputers, and embedded controllers defined.
- The stored program concept.
- Central processors and how they work.
- Types of microcomputers.
- Modern examples of embedded controllers.
- Digital signal processing.

INTRODUCTION

Whenever you hear or see the word *microcomputer*, you probably think of a personal computer. A personal computer is, of course, one type of microcomputer. But you may not be aware of other forms of microcomputers. For example, do you know that almost every piece of electronic equipment you own or use has a microcomputer in it? This type of microcomputer is called an embedded controller, microcontroller, or microcontroller unit (MCU). It is usually a single integrated circuit that performs all of the basic functions of a computer but is dedicated to a specific task. Such micros (*micro* is short for microcomputer) are in TV sets, stereo receivers, microwave ovens, CD players, DVD players, cell phones, blenders, copiers, and most other types of electronic devices. You will find them in your car (many of them), your iPod, your bathroom scale, gasoline pumps, and dozens of other things you use every day. Microcomputers do indeed make your day—you cannot live without them.

CONCEPTS AND DEFINITIONS

A microcomputer is a small digital computer that can take several different forms. It can be a single integrated circuit, or it can be a module made up of several integrated circuits on a printed-circuit board.

The two most common types of microcomputers are the embedded microcontroller and the personal computer. One special type of microcomputer is the programmable logic controller (PLC) used for industrial control (Chapter 12).

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00006-0
Copyright © 2018 Elsevier Inc. All rights reserved.

The larger microcomputers, such as personal computers and laptops, are made with a microprocessor. A microprocessor is a large-scale integrated circuit that contains most of the digital logic circuitry usually associated with a digital computer. This logic circuitry is referred to as the central processing unit (CPU). A microprocessor is a single-chip CPU.

Another common micro is called a *core*. A core is a microprocessor or microcomputer integrated with some other circuits. Today multicore micros are common. Two or more cores are used to get more processing power. Each core can run its own programs in parallel giving faster processing.

Embedded microcontrollers are complete micros on a single chip, including the CPU, memory, and input/output circuits. They are also called microcontrollers or MCUs. But in all cases, a microcomputer is an assembly of digital logic circuits, such as gates and flip-flops, that is used to process data. It is sometimes referred to as a *data processor* or simply *processor*.

Data, of course, refers to the binary numbers and words the processor works with. Processing refers to the way the data is manipulated or handled. Types of processing include arithmetic, logic, sorting, translating, editing, counting, and searching. Any action taken on the data is called processing. Processing normally implies that the data is changed in some way or is used to create new data. Data that is not processed as suggested above is dealt with in other ways. Four common ways are storing, retrieving, input, or output. The data is not changed by any of these techniques.

Storing data means putting it in a safe place, like a semiconductor memory or disk drive, where it can be accessed later. *Retrieving*, of course, is the opposite of storing, or going to get the data for reuse.

Input means taking data into the computer to be stored or processed. *Output* means sending the data from the computer to some external device. Input and output (I/O) are ways to transmit data from one place to another.

Another feature of a microcomputer is its *decision-making* capability. During processing, the computer can make decisions and alter its sequence of operation. In other words, the computer can "make up its mind" based on the state of the data or outside conditions.

For example, the computer can tell if a number is less than, greater than, or equal to another. It can choose among alternative courses of actions or say yes or no, true or false, if given enough input facts.

Another major application of computers is *control*. Computers can be used to actuate relays and solenoids or turn lights and motors off and on (see Fig. 6.1). In control applications, the computer actually determines when external devices are turned on or off. The computer serves as an electronic clock to time various operations. One example is the embedded single-chip microcontroller inside a microwave oven or a washing machine. Another example is a PLC, a special type of microcomputer used in industrial applications, that is commonly used to sense, sequence, and do time operations in a factory.

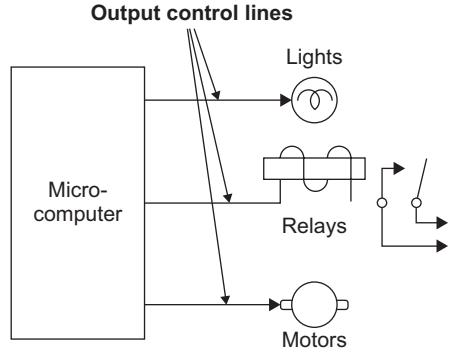


FIGURE 6.1 How a microcomputer controls external devices.

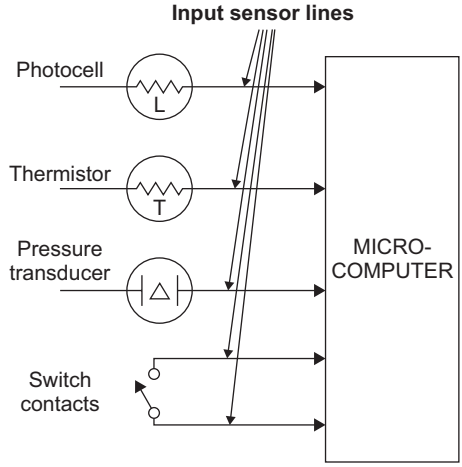


FIGURE 6.2 How a microcomputer monitors external devices.

The most important thing to remember is that the control is automatic. The micro knows when to perform the various operations that it has been assigned, because it has been programmed to do so.

To implement certain control applications, the micro must also perform a monitoring function. The micro "looks at" the process or devices being controlled to see what is happening. For example, the computer can monitor switch closures to determine physical state or position, pressure, and many other parameters. Transducers (sensors) convert the monitored physical characteristics, such as temperature or light level, into electrical signals that the computer can understand and respond to (see Fig. 6.2). In most microcontrollers or PLCs, the controlled output change takes place only if a specific input condition is sensed or not sensed. For example, if a temperature sensor indicates that the temperature has risen to a specific level, the computer will turn on a cooling fan.

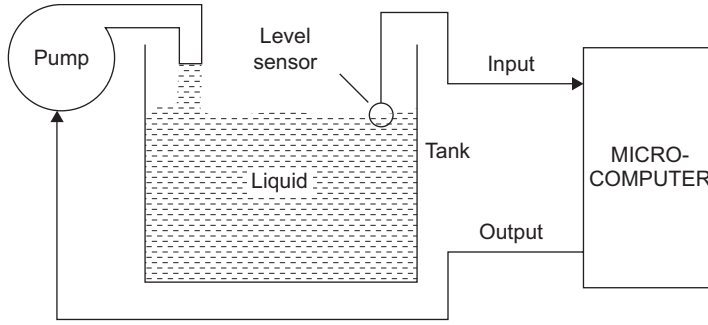


FIGURE 6.3 Controlling liquid level in a tank automatically with a microcomputer.

Micros sometimes change the control function in response to one or more of the inputs they are monitoring. For example, if the micro senses that the liquid in a tank exceeds a given level, it can automatically turn off the pump that is filling the tank. If the liquid level goes below a predetermined level, the micro detects this and automatically starts the pump (see Fig. 6.3). The key point here is that the computer makes its own decisions based on the input data that it receives. The result is full automation of some process or device.

The micro's ability to monitor and control operation may be used to automate simple processes in a toy or to operate entire factories.

COMPUTER ORGANIZATION AND OPERATION

All microcomputers are made up of four basic sections: memory, control unit, arithmetic logic unit (ALU), and I/O unit. A general block diagram of a microcomputer showing these four sections is given in Fig. 6.4. These four sections communicate with one another over multiple parallel electrical conductor data paths called a bus, as shown, to process the data or perform a control function.

Note that the control and ALU are shown together in a common structure. This is the CPU. The CPU is, of course, usually a microprocessor.

The memory is that part of the computer where data and programs are stored. The memory in any computer may contain thousands, millions, or even billions of locations used for storing numbers, words, or other forms of information.

Two primary types of information are stored in computer memory. The first type is the data to be processed. These are the codes, numbers, letters, and other forms of data to be manipulated.

The other type of data stored in memory is an instruction. Instructions are special binary numbers or codes that tell the computer what to do. Instructions specify the ways in which the data is to be processed. For instance, there are instructions that cause arithmetic operations to take place or data to be transferred from one place to another.

The instructions listed in a special sequence form a program. A program is a list of instructions that causes data to be processed in a unique way. A program

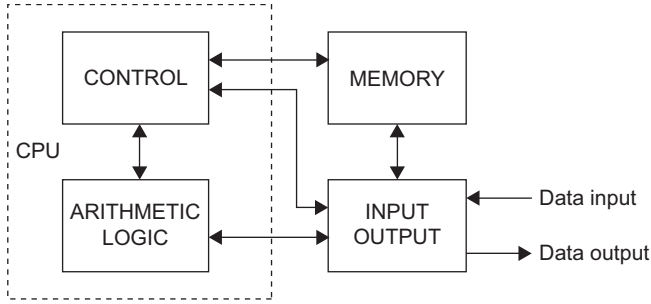


FIGURE 6.4 General block diagram of any digital computer or microcontroller.

is a step-by-step procedure that solves a problem, performs a control operation, or otherwise manipulates data according to some recipe. Programs are stored in memory along with the data that they process. In some micros there are separate memories for data and instructions. The programs that a computer uses are called software.

Data and instructions can be stored in or retrieved from memory during processing. When data is stored, we say that it is written into memory. When data is retrieved, we say that it is read from memory. A typical write operation transfers data from an analog-to-digital converter and stores it in memory. A common read operation accesses data in memory to be transferred to a liquid crystal display (LCD) screen.

Now let us look at the operation of the CPU. The control unit is that portion of the digital computer responsible for the automatic operation. The control unit sequentially examines the instructions in a program and issues signals to the other sections of the computer that carry out designated operations.

Each instruction is fetched (read) from memory by the control unit, interpreted, and then executed one at a time until the program is completed. This is called the fetch–execute cycle, which is repeated on each instruction until the program runs to completion. The execution of each instruction may call for accessing one or more data words in the memory or storing a data word in memory.

The ALU is the section of the computer that carries out many of the functions that are specified by the instructions. In other words, the ALU actually processes the data. Specifically, the ALU carries out two main types of processing: arithmetic operations (such as addition, subtraction, multiplication, and division) or logic operations (such as AND, OR, complement, or exclusive OR). For example, if an add instruction is stored in memory, the control section will fetch it, interpret it, and send signals to the ALU that cause two numbers to be added.

The ALU also performs data movement operations. It can move data or instruction words from one place to another inside the CPU, or it can carry out memory read/write or input/output operations. These are called load and store instructions.

A key part of the CPU associated with the ALU is the registers. Most ALUs have two or more registers. High-powered CPUs may have a group of 16 or more registers, called *general purpose registers* (GPRs). The registers are used to temporarily store the data being processed by the ALU and the results of the computations. Other registers in the CPU store a number called an *address* where the data or instructions are stored, store the instruction being executed, or act as a stop-off place for data into or out of the CPU.

The control section, ALU, and the registers in all micros are very closely related. They operate together and are always considered as a single unit. As indicated earlier, the combination of the control and the ALU sections is called the CPU (see Fig. 6.4). In addition, microprocessors are single-chip CPUs. Besides being called CPUs, microprocessors are sometimes called MPUs or *microprocessing units*. You will also see the expression μP used to refer to a microprocessor. The μ is the Greek letter mu, which means micro; the P means processor.

A microcomputer consists of a microprocessor (the CPU) plus external memory and I/O circuits. Or it could be an embedded controller with everything on one chip. The memory is either SRAM or DRAM for data and programs, and EEPROM or flash for the program.

The I/O unit of the computer is the set of logic circuits that permits the CPU and memory to communicate with the outside world. The I/O circuits are referred to as *interfaces*. All data transfers into and out of the computer pass through the I/O interfaces.

The external peripheral devices, or *peripherals*, connected to the I/O unit are electronic or electromechanical units that are used for data entry or data display. Data is most commonly entered into the computer through an input keyboard or a disk drive.

The output data is usually displayed on a video monitor or small LCD screen. “Hard copy” on paper is created by a printer. There are a wide variety of other external input/output devices such as scanners, voice synthesizers, and barcode readers.

In an embedded microcontroller, the peripheral devices include keyboard, ADC, DAC, sensors, magnetic stripe readers, barcode scanner, and so on. Outputs go to relays, motors, lights, and LCDs.

There are two basic ways that microcomputers are organized. One is called the Von Neumann architecture, and the other is called the Harvard architecture. The Von Neumann architecture is the older basic design we have discussed so far. Its main characteristic is that both the program instructions and the data to be processed are stored in a common memory. The Harvard architecture features separate memories for data and programs. Older micros use the original Von Neumann architecture, but the newer microcontroller chips use the Harvard architecture. Data memory is usually volatile RAM while the program or instruction memory is larger and usually nonvolatile EEPROM or flash.

OPERATIONAL DETAILS

Registers and the Arithmetic Logic Unit

The main circuit element in a CPU is the register. Usually the data to be processed by the CPU is taken from memory and stored temporarily in a register. Like a memory location, a register usually has a fixed length such as 8, 16, or 32 bits. But unlike a memory location, registers are often used to manipulate data as well as store it. That is, the register can alter or process the data in some way.

Examples of how a register can process data are shown in Fig. 6.5. A binary word in a register can be shifted one or more bit positions to the right or left, or the register may be connected as an up/down counter, so that it can be incremented (add one to the content) or decremented (subtract one from the content). A register can also be reset or cleared, thereby erasing any data in it and leaving the content zero.

Data transfers and manipulations performed on a register are initiated by individual computer instructions. For example, one instruction may cause the register to be loaded from a memory location. Another instruction may cause the word in the register to be transferred to a memory location. All data transfers are parallel, meaning that all bits are moved simultaneously from the source to the destination.

The main working register in most digital computers is called the *accumulator*. It may also be called the *A register*, *W register*, or something else. The accumulator can hold one word whose bit length is equal to that of a memory location. An 8-bit microprocessor has an 8-bit accumulator. The accumulator is part of the ALU.

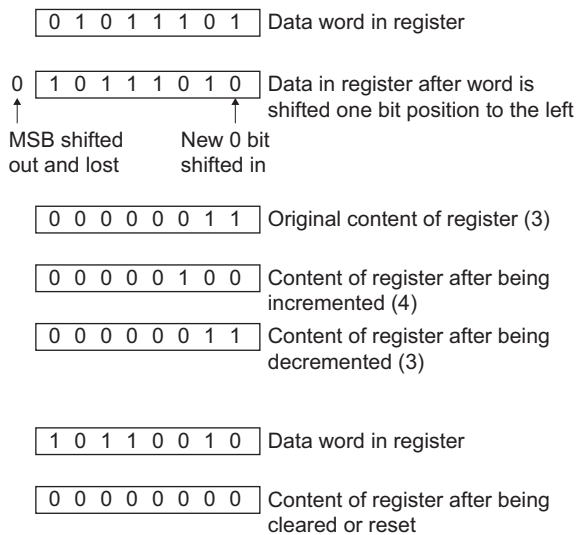

0 1 0 1 1 1 0 1
Data word in register
0
1 0 1 1 1 0 1 0
Data in register after word is shifted one bit position to the left
MSB shifted out and lost
New 0 bit shifted in
0 0 0 0 0 0 1 1
Original content of register (3)
0 0 0 0 0 1 0 0
Content of register after being incremented (4)
0 0 0 0 0 0 1 1
Content of register after being decremented (3)
1 0 1 1 0 0 1 0
Data word in register
0 0 0 0 0 0 0 0
Content of register after being cleared or reset

FIGURE 6.5 How data is manipulated in a register. Examples of shifting data, incrementing and decrementing a register, and clearing (resetting) a register to 0.

The accumulator can be loaded from memory or the accumulator content can be stored in any memory location. I/O operations with peripheral units sometimes also take place through the accumulator.

Data to be processed by the arithmetic/logic section is usually held in the accumulator. This data is fed to the ALU. The ALU is a digital logic circuit that can add, subtract, and perform a wide variety of logic operations.

The ALU is capable of processing two inputs, one from the accumulator and one from the memory of another register (see Fig. 6.6). Let us assume that you wish to add two binary numbers. To do this, you first load one of the numbers (the *augend*) into the accumulator. This is done with a load accumulator instruction that takes the number from a memory location and puts it into the accumulator. Next, an ADD instruction is executed. This causes another word (the *addend*) to be taken from memory and placed in register B. It is then added to the content of the accumulator. The sum is usually stored back in the accumulator, replacing the augend originally there.

Some microprocessors have two or more accumulator registers that share a single ALU. Two accumulators provide greater flexibility in the manipulation of data than a single accumulator. Such multiple registers simplify, speed up, and shorten a program to perform a given operation. Some sophisticated CPUs have 4, 8, 16, or even more accumulators. Usually they are referred to as GPRs or a register file. These registers can each use the ALU and act as temporary storage locations for data and the intermediate results of calculations. Instructions are provided to move data from one register to another.

In most micros, the GPRs share a single ALU. The ALU accepts only two input words and generates a single output word. The two words to be processed

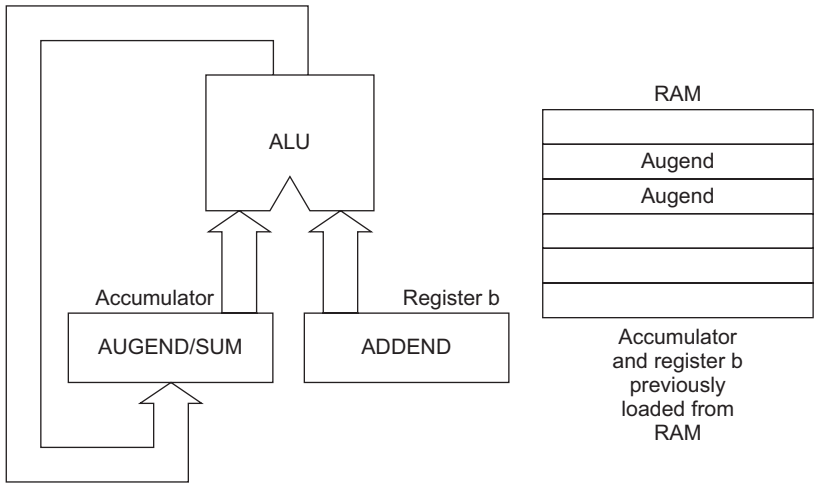


FIGURE 6.6 How ALU adds or otherwise processes two data values.

by the ALU usually come from any two GPRs or any GPR and a designated memory location. The destination of the ALU output can also be one of the GPRs in some CPUs.

Control Unit

CPUs also have several other registers, including the instruction register (IR); the program counter (PC), also called the instruction counter; and the memory address register (MAR), also called the address buffer.

The IR is used to store the instruction word. When the CPU fetches an instruction from memory, it is temporarily stored in the IR. The instruction is a binary word or code that defines a specific operation to be performed. The instruction word is also called the *op code* or *operation code*. The CPU decodes the instruction, and then executes it.

The PC is really a counter and a register. It stores a binary word that is used as the address for accessing the instructions in a program. If a program begins with an instruction stored in memory location 43, the PC is first loaded with the address 43. The address in the PC is applied to the memory, causing the instruction in location 43 to be fetched and executed. After the instruction is executed, the PC is incremented (add 1) to the next address in sequence, or 44. The instructions in a program are stored in sequential memory locations.

The MAR or *address buffer* also stores the address that references memory. This register directly drives the address bus and the memory address decoder in RAM or ROM. The MAR gets input from the PC when an instruction is to be accessed (see Fig. 6.7). The MAR can also be loaded with an address that

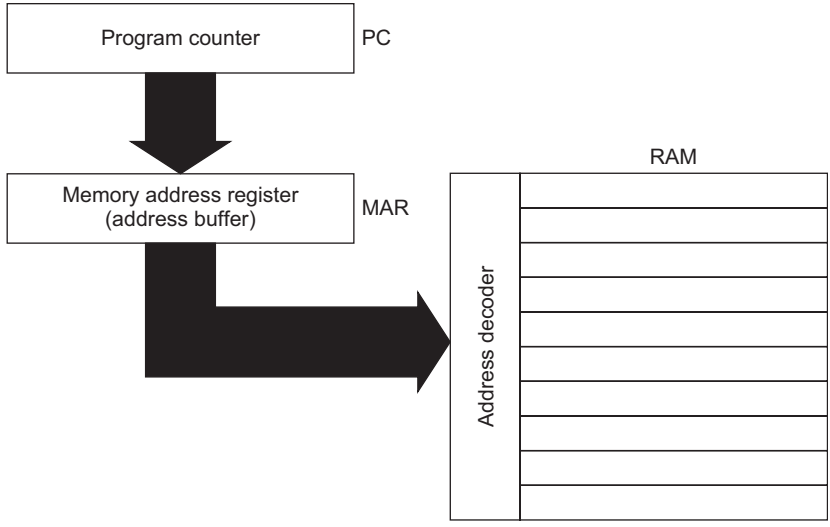


FIGURE 6.7 Program counter identifies the address in memory to be accessed.

is used to access data words stored in memory. To retrieve a data word used in an arithmetic operation, the MAR is loaded with the binary word that points to the location of that word in RAM. This address is often a part of the instruction.

It is important to note that the PC and the MAR (address buffer) have a fixed length of so many bits. And that limits the amount of memory that can be accessed. For example, with a 16-bit address register, the address bus has 16 bits to address RAM and ROM. With 16 bits, a maximum of $2^{16} = 65{,}536$ words can be addressed.

There are usually two other registers, the *flag* and *stack pointer registers*. The flag or *F register* is an 8-bit register whose individual flip-flops are set and reset by the ALU as the various arithmetic and logic operations are carried out. Each flip-flop is called a flag. As an example, there are *zero* (Z) and *carry* (C) *flags*. If the accumulator content is zero after an operation is performed, the Z flag is set indicating this condition. If an arithmetic operation (addition) results in a carry from the most significant bit (MSB) of the accumulator, the C flag is set indicating this condition. These flags can be monitored or tested by the control circuitry to change the sequence of processing.

The stack register is a 16-bit or larger register used to address a selected area of RAM known as the *stack*. This memory is used to store register contents and status information when subroutines and interrupts are used.

Instruction-Word Formats

There are three types of instruction formats used in typical 8-bit microprocessors, illustrated in Fig. 6.8. In the single-word format, the instruction is a single 8-bit word. This word is called the *op code*. The op code tells the ALU, the registers, and other elements of the system what to do. In this format, no address is used. The focus of the instruction is implied in the instruction. That is, the data to be processed is already in a location designated by the instruction. Usually the data is in a register. Typical instructions using this format are register-to-register transfer, shift data left (or right), or clear to zero.

The two-word instruction format in Fig. 6.8 requires two 8-bit words to define the operation. These two words are stored in sequential memory locations. The first word is the op code. The second word is usually an address that specifies a memory location where the data word to be processed is stored. For example, if the op code calls for an add operation, the address word designates the location in RAM of the number to be added to the contents of the accumulator. The 256 bytes of RAM can be addressed with 1 byte of address.

In some 2-byte instructions, the second byte is not the address. Instead, it is the data itself. This is called an immediate instruction since it is not necessary to address the data that is available immediately within the instruction itself.

The three-word instruction format in Fig. 6.8 is comprised of an 8-bit op code and two 8-bit address words stored in sequential memory locations. The second and third bytes together form a 16-bit address word that designates the location in RAM of the data to be processed. In the 3-byte instruction format,

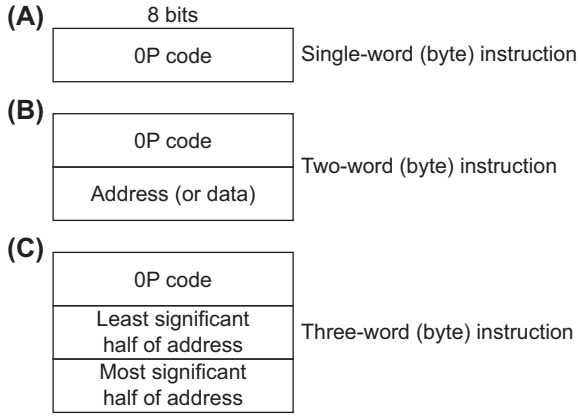


FIGURE 6.8 Three common instruction-word formats with addresses or data. *Op code*, operation code.

the first byte is the op code, the second byte is the least significant half of the address, while the third byte is the most significant part of the address. Different formats are used by other micros.

To access a word in RAM, the instruction address word must be stored in the MAR. This happens during the instruction fetch operation. When an instruction is fetched from memory, the op code is stored in the IR while the address is stored in the MAR. The instruction is then executed. The MAR usually gets its input from the PC. Once an instruction is fetched and executed, the PC is incremented.

The PC may be incremented once, twice, or three times, depending on the length of the instruction just executed. If a 2-byte instruction is executed, the PC is incremented twice so that the PC points to the address of the next instruction op code.

Program Execution Example

Now let us illustrate how a typical CPU executes a simple program. Here are a few common instructions similar to those found in any micro.

Move A to B (MOV B,A): This is a 1-byte instruction that causes the content of the accumulator (A) to be moved to register B. The content of the accumulator is not erased.
Load Accumulator (LDA): This is a 3-byte instruction that takes the content of the address specified by the second and third bytes and loads it into the accumulator.
Add Immediate (ADI): This is a 2-byte instruction that takes the content of the second byte of the instruction and adds it to the content of the accumulator. The sum is stored in the accumulator, replacing the number that was there previously.
Halt (HLT): Halt is a 1-byte instruction that stops processing.

Note that we refer to each instruction by a three-letter abbreviation called a *mnemonic*.

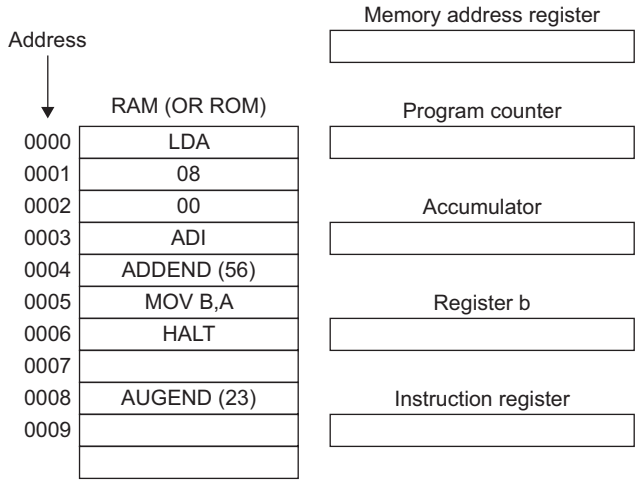


FIGURE 6.9 Example of program stored in RAM for execution using various CPU registers.

Fig. 6.9 shows a complete CPU and the RAM containing a simple program. The first instruction in the program is the LDA stored in location 0000.

To begin the execution, the address of the first instruction is loaded into the PC that points to the location of the instructions in RAM.

Next, the content of the PC is transferred to the MAR that addresses RAM. The LDA instruction op code is fetched and stored in the IR. The address bytes of the LDA instruction in locations 0001 and 0002 are then transferred to the MAR. The address of the data to be loaded into the accumulator in bytes 2 and 3 is 0008. The desired data word in location 0008 is retrieved and loaded into the accumulator. This is the augend (23).

After the LDA instruction is executed, the number 23 is stored in the accumulator. Next, the PC is incremented three times. The ADI instruction is then fetched and stored in the IR. The number to be added is stored in location 0004.

This is an Add Immediate instruction where the second byte contains the data, in this case the addend (56). The number in location 0004H is 56, which is added to 23 in the accumulator, creating the sum 79. The mnemonic of the next instruction to be executed is MOV B,A in location 0005.

The sum in the accumulator is then moved to the B register by the MOV B,A instruction. The content of the accumulator is not changed when data is transferred to the B register.

The PC is incremented once since the HLT is a 1-byte instruction.

As you can see by this step-by-step analysis of the execution of a computer program, there is nothing mysterious about its operation. The CPU simply fetches and then executes the sequentially stored instructions at very high speed until the operation is complete. This process is sometimes referred to as the *stored program concept*.

Microcomputer Buses

Data transfers inside a microprocessor take place in parallel. This means that all bits in a word are transferred simultaneously from one place to another. It takes only a few nanoseconds (one billionth of a second) for all data bits in one register to be moved to another register.

The parallel data transfers take place over a data bus. A bus is simply multiple parallel electrical connections from a source to a destination. A number of these buses are contained within the CPU and are known as internal buses.

Microprocessors usually have three major buses—a *data bus*, an *address bus*, and a *control bus*. These are made available to external circuits in some micros. A typical 8-bit CPU has an 8-bit data bus and a 16-bit address bus. The data bus sends data to and from the CPU, RAM, ROM, and I/O sections. All data transfers between the CPU and memory or I/O sections take place over the data bus. The address bus drives all of the memory and I/O devices.

When an instruction is fetched from RAM or ROM, it is transferred over the data bus from the memory into the IR. Any data word retrieved from memory or a peripheral device via the input section also passes over the data bus into the accumulator or GPR.

When a store instruction is executed, the word in the accumulator is transmitted over the data bus into RAM. Data can also be transferred from the accumulator over the data bus to an external device such as an LCD. Or, data from an input device such as a keyboard passes over the data bus and is placed into the accumulator. The important point here is that data can move in either direction over the data bus. We say that it is a *bidirectional bus*.

Another key point is that the data bus can be connected to only one data source at a time. Data can originate only at a single source, but it can be sent to one or more destinations. To accomplish this, circuits called *bus multiplexers*, or *three-state line-driver circuits*, are used to connect or disconnect the various data sources to or from the bus. Fig. 6.10 illustrates this concept.

The address bus is a unidirectional bus. It transfers an address from the CPU to all external circuits (memory and I/O). Address words are produced in the CPU. The PC generates the address that points to the instruction to be fetched. The content of the PC is transferred over a parallel 16-bit internal address bus to the MAR or address buffer. The output of the MAR or address buffer is the address bus.

The control bus consists of numerous signals generated by the microprocessor and used to initiate various memory or I/O operations. The control bus also contains input lines from external circuits that tell the CPU what to do and when. The number of control signals varies from CPU to CPU.

POPULAR MICROCOMPUTERS

The first practical microprocessors and microcomputers became available in the mid-1970s. Over the years lots of different models have been developed. As semiconductor processing technology has improved during the past 40 years, it

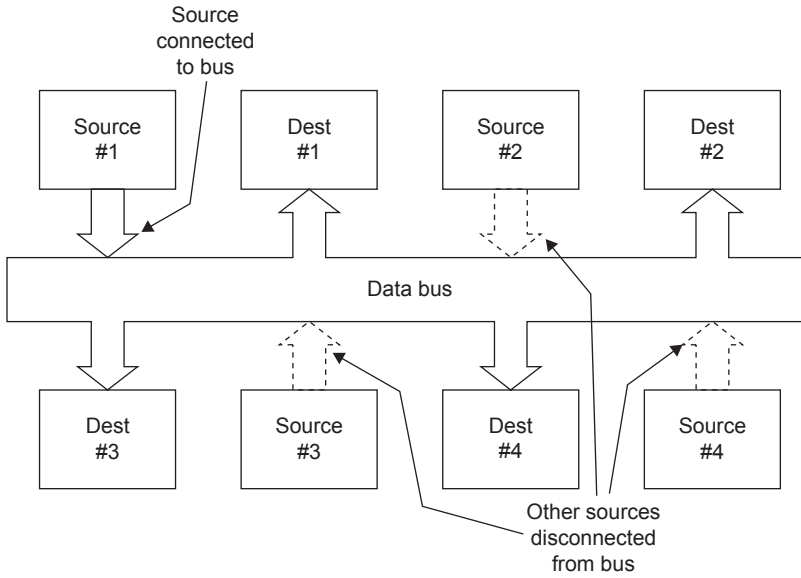


FIGURE 6.10 Only one source may transmit at a time on a bus. Others are disconnected. All destinations can receive the transmitted data. *Dest*, destination.

has become easier and cheaper to put more circuits on a chip plus the memory that earlier was always external. And processing speeds have multiplied many times over. Today's embedded controllers are indeed complete computers on a chip and they run at very high clock rates. And their cost is low. In high-volume manufacturing, an embedded controller can cost less than $1.

Most of the initial processors were 8-bit devices. These are still popular today. Larger, faster processors are available for not much additional cost. 16- and 32-bit processors are commonplace. Even 64-bit devices are available if needed. Many are individual chips, while others are available only as cores on a larger systems chip. Following is a summary of a few of the most widely used processors.

8- and 16-Bit Microcontrollers

8051

The 8051 is one of the oldest but still widely used. It was originally developed by Intel in the late 1970s and 1980s. It is still around and available from a half dozen or more companies. The more recent versions are faster and have more memory and I/O features than the original. Original clock speeds were only 8–12 MHz, but today you can get models with a clock rate up to 100 MHz.

A general block diagram of the 8051 is given in Fig. 6.11. The 8051 features an internal RAM of 128 or 256 bytes but can handle 64 or 128 KB

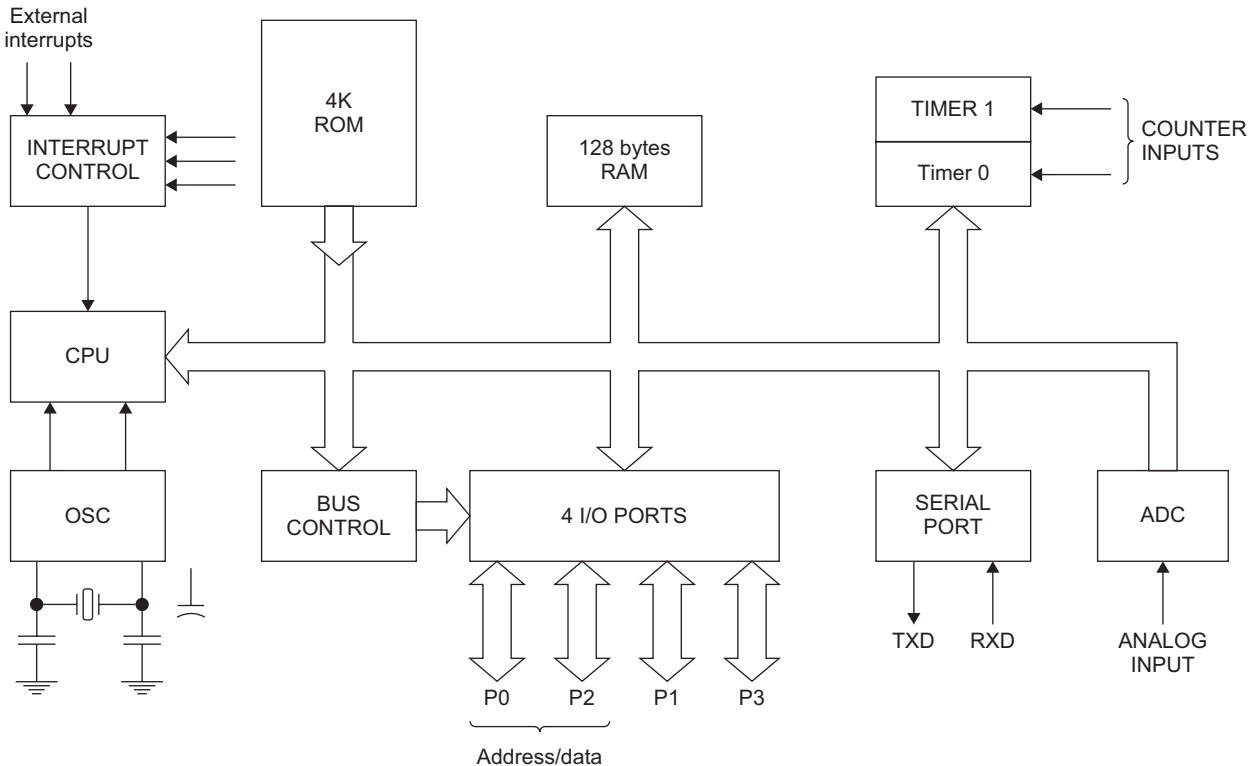


FIGURE 6.11 General block diagram of 8051 microcontroller. It is very similar to most other controllers in terms of major circuits and their interconnections.

of RAM externally. The internal ROM can be had from 512 bytes to 128 KB. Some models also feature flash memory. As for I/O ports, the figure shows four 8-bit parallel I/O ports. You can get a standard serial port called a UART, and more specialized I/O ports such as SPI and I^2C. See the Interfaces sidebar in this chapter. Many models also come with an internal 10- or 12-bit ADC.

A few other items in this diagram that were not previously discussed are the clock, interrupts, and timers. The *clock* is an oscillator that controls all operations in the micro. Its frequency is usually set by an external crystal that maintains a precise and stable frequency. The higher the frequency, the faster the operations. Fast is good.

An *interrupt* is, as its name implies, an external signal that can interrupt the CPU when an important event occurs. It can signal the CPU of the event and even cause the CPU to stop executing the current program and jump off to another program to deal with the interrupt.

Timers are usually just one or more up/down counters that can be programmed with various count values. These are used to implement count functions in programs and to provide timing operations for I/O operations. Most controllers have one or more timers.

PIC Processors

Microchip Technology makes one of the most widely used 8-bit controllers. Called PIC processors, they are extremely simple and cheap. There are hundreds of versions with different memory sizes and configurations and various mixes of interfaces. One of the simpler versions is the 16C54. It has a single working register, W, that is the accumulator. It uses a bank of 24–73 registers for RAM. ROM for program storage ranges from 512 bytes to 2 KB. I/O occurs via 4- or 8-bit parallel ports. Larger versions have more RAM and more ROM, higher clock speeds, a built-in ADC, and special network interfaces like CAN. Several 16-bit versions are also available.

MPS430

The MPS430 is a line of 16-bit microcontrollers from Texas Instruments. It has 16 GPRs and a maximum clock speed of 25 MHz. There are multiple versions each with a different mix of memory types including up to 512 KB of flash and 64K of SRAM. Some models include a new type of nonvolatile memory called ferroelectric random access memory (FRAM). FRAM uses a cell similar to a standard DRAM cell that stores bits in a capacitor. Using a ferroelectric dielectric in the capacitor allows data to be retained when power is removed. The MPS430 has an ADC on board, a DAC, timers, PWM outputs and all the common serial interfaces. It is a popular chip because its ultra low power consumption makes it ideal for portable and battery-powered devices.

32- and 64-Bit Processors

As it turns out, it is almost as cheap and easy to make a 32-bit processor as it is to make an 8-bit device. For that reason, for a few cents more, designers can make their products faster and more powerful by selecting a 32-bit device. With this many bits being processed at the same time, it is possible to move more data faster, compute with increased resolution, and to perform much more complex operations faster and easier. 32-bit processors can also address much more memory. A few years ago, 32-bit processors were reserved for only the largest or most critical of needs. Today, the 32-bit processor is almost as widely used as the 8-bit processor.

Three devices account for most applications. They are made by ARM Holdings, NXP, and MIPS. ARM is the name of a British company that invented a supersimple, fast, and flexible 32-bit processor that does everything well at very low cost. It is referred to as a reduced instruction set computer (RISC) processor. It has a few simple instructions but is extremely fast. ARM does not actually make chips, but instead licenses the design to others. There are several vendors of ARM processors but most of them are actually cores that are integrated on chip with other circuits to form a system on a chip. With over 75% of the market share, you are sure to encounter an ARM device sooner or later. Chances are you own at least one inside a product such as a cell phone, which is where most are used.

NXP's PowerPC is another popular 32-bit processor. Many embedded versions have since been made. Its primary usage is in communications, networking, automotive, and industrial applications.

For really super processing power, the MIPS processors are a popular choice for certain embedded applications. These devices come in 32-bit as well as 64-bit models, in case you really have a hot application for which nothing else will do. The MIPS processors are great at advanced math and have excellent resolution.

Microcontroller Interfaces

An *interface* is the circuitry that connects an embedded controller to the outside world. Initially, all I/O in early micros was just the parallel data and address buses extended to accommodate additional I/O circuitry. Today, much of the I/O interface circuits are put right on the same chip with the rest of the micro. Following are the most widely used interfaces you are likely to encounter. All of these are serial interfaces. Parallel I/O is still used, but today the preference is serial I/O because of fewer interconnecting lines.

RS-232/UART—This universal asynchronous receiver–transmitter is actually the physical circuitry implementing a popular serial interface standard referred to as RS-232. It was originally developed for connecting computers to teletype machines and early video terminals. It is still used today, especially for connecting to industrial equipment for monitoring or control. You will hear this interface called a serial port.

Continued

Microcontroller Interfaces—cont'd

The RS-232 interface sends and receives data in bytes (8 bits) plus two extra bits, called Start and Stop bits, that tell the receiving device when the data begins and ends (see Fig. 6.12). The logic levels are −3 to −25 V for a binary 1 and +3 to +25 V for a binary 0. Typical voltage levels are in the 5- to 12-V range. The data rate is slow, typically from 300 bps to 115.2 kbps. Standard data rates are used, so no clock signal is needed. Common speeds are 2400, 9600, and 19,200 bps. The physical communications medium is a two-wire (signal plus ground) cable that can be up to 50 ft long. Special 9- and 24-pin connectors are part of the standard. Many PCs and laptops still have a 9-pin RS-232 port.

I^2C—Shorthand for interintegrated circuit or I squared C, this is a low-speed serial bus that is used for sending data from one chip to another on the same PC board or over short cables between two pieces of equipment. The data rate is typically in the 10–400 kbps range, but a faster version (3.4 Mbps) is available. Speeds rarely exceed 100 kbps. Only three wires are needed, data, a clock signal that controls the data transfer, and a ground.

SPI—This is the serial peripheral interface. It uses four wires, data in, data out, clock, and a select signal that determines whether a device is a master or slave and either sending or receiving data. A fifth connection is ground. It is much faster than the I^2C interface, with speeds up to 20 Mbps.

CAN—This is controller area network serial bus in an interface used to link micros together in small networks. It is used in automotive and industrial applications. The usual cable is twisted pair and a ground. Speeds range from 10 kbps to 1 Mbps with 20 kbps being typical. The data is sent in specifically formatted frames as determined by a standard protocol. It uses start and stop bits like the RS-232 and some similar control codes defined in ASCII. It also includes error detection and correction capability, so it is very reliable.

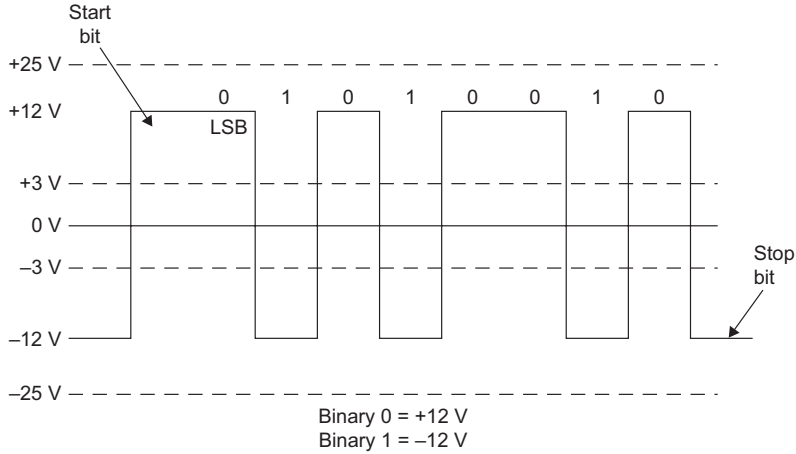


FIGURE 6.12 ASCII letter "j" being sent over an RS-232 interface using a UART.

Continued

Microcontroller Interfaces—cont'd

USB—The universal serial bus is the most common PC interface for peripherals including keyboard, mouse, printer, flash drive, external disk, and so on. It is also used in some embedded micros. The interface uses two wires but also includes 15 V DC and ground. Version 2.0 provides speeds to 480 Mbps over cables no longer than 16 ft. A new higher-speed version 3.0 is also available with speeds up to 5 Gbps. Data is sent in bytes in packets according to a unique protocol.

RS-485—This is an interface widely used in industrial applications. It uses twisted pair cable that can be up to 4000 ft long. The cable is actually a bus to which many devices can be attached. Data rates can be up to 10 Mbps for shorter lengths. Various protocols may be used.

DIGITAL SIGNAL PROCESSING

Digital signal processing (DSP) is the technique of programming a microcomputer to perform operations normally carried out by analog or linear circuits. The method is illustrated in Fig. 6.13. Assume you want to process an analog signal by filtering. You could use a hardware filter made up of inductors and capacitors or resistors and capacitors. Another way to do it is with DSP. The analog signal to be filtered is first digitized with an ADC and the resulting data stored in an RAM. This data is then acted upon by a processor programmed to perform a filter function. Special mathematical algorithms have been developed to do this. The resulting calculations generate new data that is also stored in the RAM. This new data is then sent to a DAC where it is converted back to an analog signal. The result is that the signal is filtered

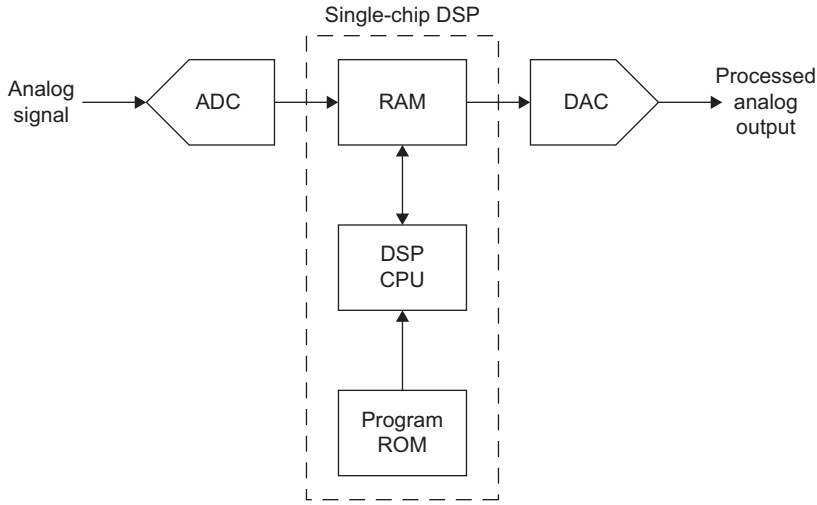


FIGURE 6.13 Basic makeup of digital signal processor and its ADC and DAC I/O.

as if were processed by an electronic circuit of capacitors and inductors. The processing was mathematical.

There are many other operations that can be performed by DSP. Filtering is the main application, but you can also do things like modulation and demodulation as needed in wireless applications. It will perform other things such as data compression, equalization, tone control, and even frequency analysis. Using a program called the fast Fourier transform, the DSP can analyze a signal and tell you exactly what frequency components are in it. It identifies the harmonic frequencies and their various amplitudes and phases just as in a frequency–domain plot.

The big question is why use a complicated technique such as DSP when you can do it with simple analog/linear hardware? Probably the best answer is "just because we can." With cheap single-chip processors, DSP is often no more expensive than an equivalent analog circuit. Since everything else is digital these days, it makes some sense to do as many analog functions digitally as well. But the best reason is that DSP provides superior results over analog methods. Filtering is substantially improved with better selectivity that was not possible with analog filters.

While DSP can be programmed on any processor or controller, it is best done on special DSP chips designed for the purpose. They use special architectures and processing schemes to speed up and improve the processing over standard conventional processors. A good example is that DSP chips implement a multiply and add or accumulate function, called MAC, that is common to most DSP processes. The MAC has to be programmed in a standard processor, but in a DSP chip it is implemented with special hardware that speeds up the process and simplifies programming. Some more conventional processors also incorporate DSP instructions to facilitate DSP operations. It is also common to implement DSP in an FPGA or in custom digital logic inside a larger IC.

Today, DSP is found in most electronic products today, such as TV sets, cell phones, MP3 players, cable modems, and many other common products.

Chapter 7

Radio/Wireless

The Invisible Cables of Modern Electronics

In this Chapter:

- The oldest electronic application.
- What are radio waves?
- The electromagnetic frequency spectrum.
- The hardware of radio: transmitters, receivers, and antennas.
- Two-way radio applications.
- Satellites.
- Radio telescopes.

INTRODUCTION

First they called it wireless. Then they called it radio. Today, the term *wireless* is trendy again. Whatever you call it, radio is communication over a distance without any physical connection. Radio is cool because it is completely silent and invisible. It can occur over a distance of only a few feet, all the way around the world, or between planets and spacecraft. Radio, despite the fact that it has been around for over a century, and the fact that we take it for granted on a grand scale, is truly black magic. When you finish reading this chapter, you will know how this magic works.

RADIO COMMUNICATION SYSTEMS

Radio is an electronic communications system. All electronic communications systems have the basic form shown in Fig. 7.1, whether it is a wired or wireless system. The information to be communicated, usually voice, is first converted into an electrical signal by a microphone. That signal is then processed by the circuits in a transmitter (TX) and then sent via a communications medium to a receiver (RX) that processes the signal and converts it back into voice by a speaker or headphones. In the telephone system, the communications medium is a cable made of copper wire. In a cable TV system, the medium is a coaxial cable, twisted-pair cable, or fiber optic cable. But in radio, the communications

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00007-2
Copyright © 2018 Elsevier Inc. All rights reserved.

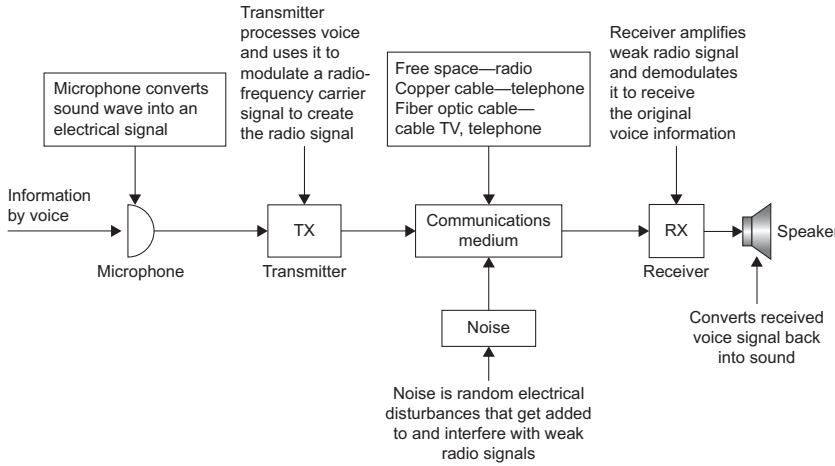

Transmitter processes voice and uses it to modulate a radio-frequency carrier signal to create the radio signal
Receiver amplifies weak radio signal and demodulates it to receive the original voice information
Microphone converts sound wave into an electrical signal
Free space—radio
Copper cable—telephone
Fiber optic cable—cable TV, telephone
Information by voice
TX
Communications medium
RX
Speaker
Microphone
Transmitter
Receiver
Noise
Converts received voice signal back into sound
Noise is random electrical disturbances that get added to and interfere with weak radio signals

FIGURE 7.1 Model of electronic communications system.

channel is free space. The radio signal travels from one place to another almost instantaneously, and it passes right through most obstructions such as walls, buildings, smog, trees, and even people. Note that noise is added to the signal as it passes through the channel or medium.

Noise

Noise is any random electrical voltage that interferes with the weak radio signal. Noise comes from the atmosphere, space, human-made objects, and electronic components. Atmospheric noise is lightning. Space noise comprises random signals from the Sun and remote stars. Human-made noise comes from electrical power generation, distribution, and switching. It also comes from fluorescent lights, motors, auto ignitions, and many other sources. The worst noise comes from the electronic components that actually process the weak radio signal. Resistors, transistors, and integrated circuits generate random noise because of thermal agitation. Heat produces random movement of the electrons in the components, and that produces a noise voltage which is added to the radio signal. Even though noise voltages are very small (microvolts or nanovolts), they are still large enough to interfere with and in some cases obliterate the very small received radio signal. In most radio systems, it is noise that limits intelligibility, transmitted data speed, and transmitted distances.

THREE BASIC WAYS OF COMMUNICATIONS

Radio communications systems work in one of three basic ways: simplex, half duplex, and full duplex (see Fig. 7.2).

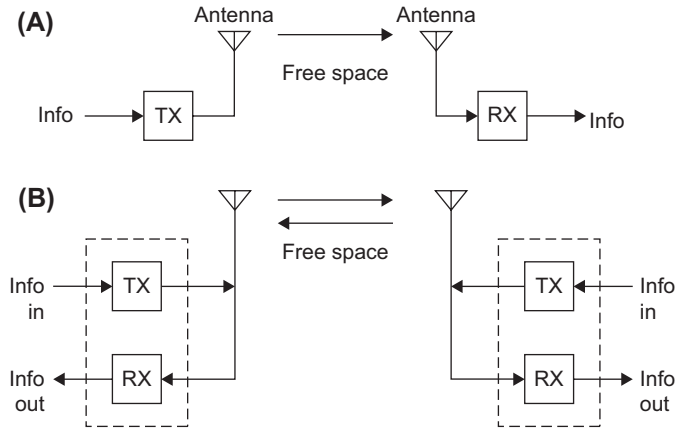


FIGURE 7.2 Ways of communicating. (A) Simplex—one way and (B) duplex—two way: half—alternating send/receive and full—simultaneous send/receive.

Simplex

Simplex is one-way communications. Examples are radio broadcasting, paging, and remote control. A radio telescope is also one-way: there is a transmitter at one end and a receiver at the other.

Half Duplex

Duplex means two-way, and most radio communications are really two-way affairs. There is a transmitter and a receiver at both ends of the communications system. Both parties can send and receive. And there are two types of duplex systems: half duplex and full duplex.

In half-duplex systems, only one party can transmit at a time. Those communicating with one another take turns talking. This is the kind of radio where you have to say "over" or "come back" after you finish speaking to let the other party know that it is time for her or him to talk. Citizens band (CB) radio is like this. Most two-way communications services (police, fire, taxi, aircraft, marine, etc.) use this method because it is cheap and simple. Fax machines are half duplex. Most computer modems are half duplex.

Full Duplex

Full duplex is more complex and expensive. This is two-way radio where both parties can both send and receive simultaneously. Probably the best example of this is a cordless or cellular telephone. It is great to be able to talk and listen at the same time.

WHAT IS A RADIO WAVE ANYWAY?

Any discussion of radio always gets around to this basic question. How do you describe something that you cannot see, feel, or hear? You imagine it.

Electric and Magnetic Fields

A radio wave is an invisible force field that is made up of both a magnetic field and an electric field. In combination, we call them an *electromagnetic field*. We cannot see or feel them, but we can experience their effects. In Chapter 2, electric and magnetic fields are described briefly. To review, a magnetic field is a force generated by a magnet, either a permanent magnet or electromagnet. Current flow in a wire or other conductor produces the magnetic field. Invisible magnetic flux lines emanate from the magnet and may influence objects in or near them.

An electric field derives from a voltage, or what we call a *potential*, across two conductors. The attraction of the positive and negative charges across an open space introduces another kind of invisible field that can also influence external objects.

Now if you combine these two types of fields into a self-supporting entity, you would have an electromagnetic field or *radio wave*. We create a radio signal with the circuits in a transmitter, but it is the magic of a device called an *antenna* that produces the combined electric and magnetic field that we refer to as a radio wave.

In the 19th century, a British scientist named James Clerk Maxwell figured out that if you generate a changing electric field, it would, in turn, generate a magnetic field. If the magnetic field is changing and moving forward, it will generate an electric field. The two fields support or regenerate one another as they change and move outward from the antenna that produces them. Maxwell expressed his theories in his famous mathematical equations that form the foundation of radio and light transmission.

Trying to draw a picture of a radio wave is somewhat like trying to draw a picture of the wind. Nevertheless, Fig. 7.3A is an attempt. Try to think in three dimensions. Current flow in the antenna wire creates the magnetic field lines. The voltage across the two segments of the antenna produces the electric field lines. The picture is somewhat simplified if we just show the field lines as in Fig. 7.3B. The electric and magnetic field lines are always at right angles (90 degrees) to one another. The radio wave moves in a direction at a right angle to both field lines, in this case either into or out of the page. As it gets some distance from the antenna, it becomes self-supporting. That is, the magnetic field sustains the generation of the electric field and vice versa.

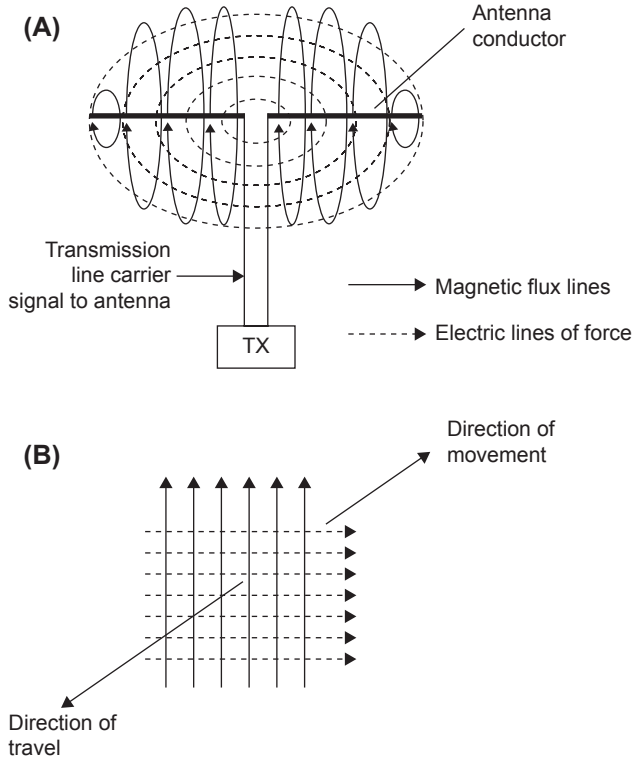


FIGURE 7.3 How an antenna creates a radio wave. (A) Antenna produces both electric and magnetic fields. (B) The electric and magnetic field lines are at a right angle to one another and to the direction of radiation.

Polarization

Polarization of a radio wave means how it is oriented with respect to the surface of the Earth. If the electric field is vertical to the surface of the Earth, the wave is vertically polarized. If the electric field is horizontal to the Earth, the wave is horizontally polarized. It is the orientation of the antenna generating the radio signal that determines the polarization. A vertical antenna produces vertical polarization, and a horizontal antenna produces horizontal polarization. For the best reception, the transmitting and receiving antennas should both be either vertical or horizontal.

There is also circular polarization. Some antennas make the signal rotate clockwise or counterclockwise as the signal travels from transmitter to receiver. Clockwise rotation, as viewed from the transmitter, is called right-hand circular polarization. Counterclockwise rotation is called left-hand circular polarization.

Signal Speed

Radio waves travel at the speed of light in space. That is 300,000,000 m/s or 186,410 miles/s. So while radio transmission is not instantaneous, it is pretty fast. Just as an example, to transmit a signal to the moon that is 250,000 miles away takes 250,000/186,400 = 1.34 s.

Signal Strength

As the radio wave gets farther and farther from the antenna, it gets weaker and weaker. The power in a radio wave, in fact, decreases by the square of the distance from the antenna. For example, doubling the distance decreases the received power by two squared (2^2) or four. Even when the transmitter puts many hundreds or thousands of watts of power into the antenna, the signal received at a distance is many times smaller. Typical radio signals are usually expressed in terms of microwatts (1-millionth of a watt) or nanowatts (1-billionth of a watt).

As the radio wave encounters a receiving antenna, the magnetic and electric fields induce a voltage into the antenna. This tiny voltage is then amplified and translated back into the original information signal by the receiver.

ELECTROMAGNETIC FREQUENCY SPECTRUM

The radio signal applied to the antenna by the transmitter is a sine wave. Remember that all sine waves have both an amplitude and a frequency. Frequency is stated in terms of cycles per second or hertz (Hz). Radio transmissions can take place over a very wide frequency range. We call this range the *electromagnetic frequency spectrum*. It extends from approximately 10 kHz–300 MHz. Fig. 7.4 shows a diagram designating the major divisions of the electromagnetic spectrum.

The electromagnetic spectrum is in free space, not only here on Earth but also throughout the universe. The spectrum space may be used by anyone and, in fact, on Earth we all share it. The spectrum is divided up and used for many different radio services. It is also partitioned such that various frequency ranges are assigned to or used by different countries for their various radio services. In many cases, portions of the frequency spectrum are shared concurrently among several countries. This allocation of the frequency spectrum is necessary to prevent radio stations from interfering with one another.

In the United States, the frequency spectrum is regulated by the Federal Communications Commission (FCC). Congress established the Communications Act of 1934, which has subsequently been amended to permit the FCC to regulate all forms of radio and wired (telephone, cable TV, etc.) communications services. The National Telecommunications Information Administration (NTIA) manages the spectrum for the government and the military. Throughout the world, the frequency spectrum is allocated and managed by a worldwide organization known as the International Telecommunications Union (ITU).

The various areas of the frequency spectrum are assigned to different types of communications services. For example, in the LF range, most communications

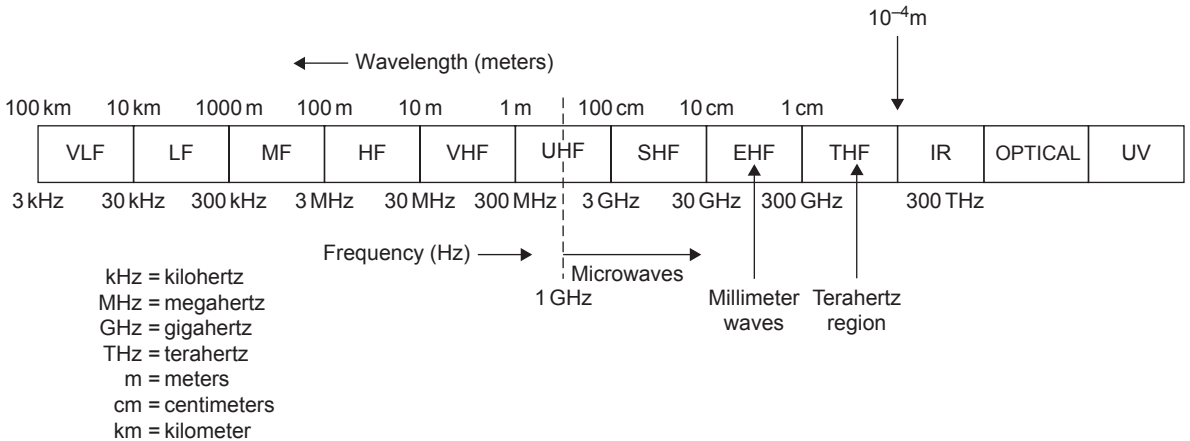


FIGURE 7.4 Electromagnetic frequency spectrum.

Major Segments of the Frequency Spectrum

30–300 kHz—Low frequencies (LFs)
300 kHz–3 MHz—Medium frequencies (MFs)
3–30 MHz—High frequencies (HFs) or shortwaves (SWs)
30–300 MHz—Very-high frequencies (VHFs)
300 MHz–3 GHz—Ultrahigh frequencies (UHFs)
3–30 GHz—Superhigh frequencies (SHFs)
30–300 GHz—Extremely high frequencies (EHFs)
300 GHz to IR—Tremendously high frequencies (THFs) or the terahertz (THz) region
Note: One terahertz is 1000 GHz.

services are navigational systems used by the Coast Guard and military. The AM broadcast band (530–1710 kHz) is in the MF range. SW radio broadcasts, CB radio, amateur radio, and a variety of other communications services are in the 3–30 MHz or HF range.

One of the most widely used areas of the spectrum is the VHF range from 30 to 300 MHz. Virtually all two-way radio communications for marine, aircraft, mobile, and other services are in this range. FM broadcasting (88–108 MHz) and TV channels 2 through 7 are also in this region.

The UHF frequency range, from 300 to 3000 MHz (3 GHz), also contains a wide variety of communications services. It includes two-way mobile radio, TV, and cellular telephone.

Frequencies above 1 GHz are designated as microwaves. In the microwave region between 1 and 3 GHz are satellite and navigational systems. For example, the widely used global positioning system (GPS) operates in this range. This area is also occupied by the newer cellular telephone service and wireless networks such as Wi-Fi and Bluetooth.

The frequencies from 30 to 300 GHz are called millimeter waves because their wavelength is in millimeters. These frequencies are typically used only by satellite and radar systems. Other services are point-to-point wireless data services and cellular backhaul. The forthcoming fifth generation (5G) cell phone system will the use millimeter wave bands. Some short-range wireless devices have also been defined for the 60-GHz range. These are used in consumer applications as well as in faster wireless networks. Automotive radars use frequencies in the 76–81 GHz range.

Critical Issue: Spectrum Space

There is only so much radio spectrum space and we must all share it. It is a true natural resource. That is why spectrum space is regulated by governments. But we have just about used it all up. Virtually every hertz of space is spoken for. Diverse radio services compete for space. In some cases, an old service must die before a new one can begin. Sometimes space is stolen from one service to give to another,

Critical Issue: Spectrum Space—cont'd

such as in the mid-1980s when the upper UHF TV channels were sacrificed to make room for cellular telephones. Lately, the US government has been selling space to the highest bidders for new cell phone and other wireless services. During the recent switchover to digital TV in the United States, a huge chunk of the spectrum was freed up (108 MHz, from 698 to 806 MHz) as TV stations abandoned this region. Known as the 700-MHz band, it was auctioned off by the government for billions for more cell phone spectrum as well as broadband wireless services.

The trend has been to push higher and higher in the frequency range to find more space. During the past several decades, the microwave region (above 1 GHz) has been developed. This region, in the UHF, SHF, and EHF ranges, was previously used only for radar and satellites. But now it is being used and developed for digital cell phones, navigation, high-speed networking, broadband (Internet) wireless, and digital TV.

Beyond the millimeter wave range above 300 MHz is the terahertz region, infrared (IR) and optical spectrum. That is, above 300 GHz, the electromagnetic radiation becomes light, namely IR, visible light, and ultraviolet light. But that 'is another story altogether. IR is widely used for wireless connectivity as most TV and other remote controls use it.

Wavelength

While we normally use frequency to refer to location of a radio signal in the spectrum, sometimes you will hear about frequencies or ranges of frequencies designated by wavelength.

Wavelength is the actual physical length of a radio wave. It is the amount of space the wave occupies. Specifically, wavelength is the length of one cycle of the sinusoidal variation of the electromagnetic fields. If we could see the electric and magnetic fields, we could measure the distance between the maximum intensity points in meters (1 m = 3.28 ft or 39.37 in.). This is the wavelength. Wavelength is also the distance that the radio wave travels in the time of one cycle.

You can determine the wavelength of a radio signal with the following simple formula:

$$\lambda = 300,000,000/f$$

Wavelength is represented by the Greek letter lambda (λ), and frequency in hertz is designated by the letter "f." The value 300,000,000 is the speed of light of a radio wave in meters per second in free space. (This translates to a speed of 186,410 miles/s.)

A radio signal with a frequency of 150 MHz is expressed in hertz as 150,000,000 Hz. Therefore,

$$\lambda = 300,000,000/150,000,000 = 2 \text{ m}$$

If we give the frequency in megahertz, the formula can be shortened to:

$$\lambda = 300/f$$

Continued

Wavelength—cont'd

For example, we can calculate the wavelength of the SW or HF part of the spectrum (3–30 MHz) as follows:

$$\lambda = 300/3 = 100 \text{ m}$$

$$\lambda = 300/30 = 10 \text{ m}$$

If you rearrange the formula, you can also find the frequency if you know the wavelength:

$$f = 300/\lambda$$

What is the frequency of the 25-m band?

$$f = 300/25 = 12 \text{ MHz}$$

RADIO WAVE PROPAGATION

Propagation refers to the way in which a radio signal travels from the transmitting antenna to the receiving antenna. The way the signal behaves is directly related to its frequency.

Low and Medium Frequencies

For example, in the low-frequency and medium-frequency ranges, the radio signals tend to hug the Earth as they move from transmitter to receiver. These ground wave signals can only travel relatively short distances because they are absorbed and attenuated by the Earth, trees, buildings, and other obstructions. Depending on the frequency of operation, transmitter power, and the nature of the terrain, distances are limited to several hundred miles. Distances can be extended with greater power or if the signal travels over water.

High Frequencies

In the HF or SW frequency range, the ground waves are extremely weak and travel only short distances, usually several miles. Instead, propagation is by way of refraction of the ionosphere. The ionosphere is an electrified area above the Earth located from approximately 30–250 miles above the Earth. The Sun ionizes the gases in the air, thereby giving them electrical characteristics. The closer the ionosphere to the Sun, the greater the degree the ionization. The ionosphere is actually several different layers or ionization levels as shown in Fig. 7.5. The upper layers have greater ionization than the lower layers. Obviously, the degree of ionization is determined by whether it is day or night. During the daylight hours, the ionosphere is highly charged electrically. At night, the ion layers essentially disappear.

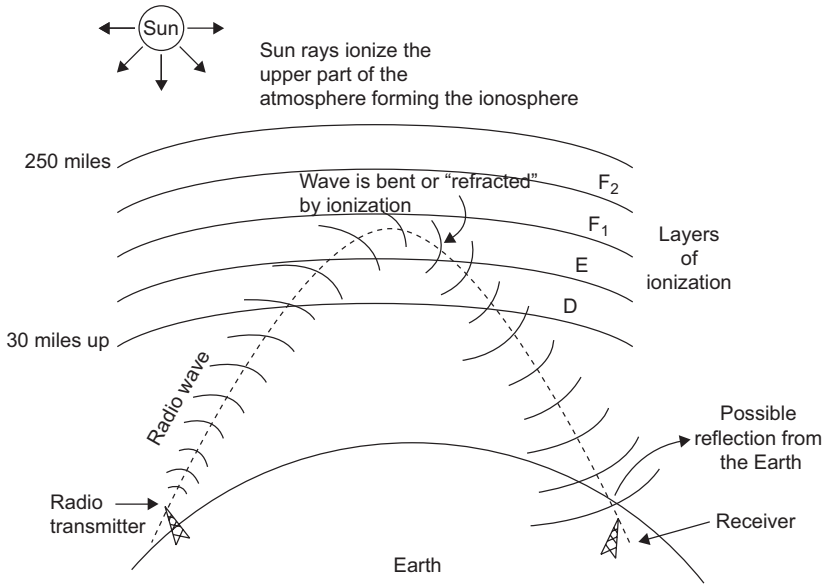


FIGURE 7.5 Radio propagation of shortwaves.

A radio wave in the 3- to 30-MHz range is transmitted up to the ionosphere where it is refracted or bent by ionization. The degree of bending depends on the frequency of operation and how high in the ionosphere the radio wave penetrates. In most cases, the radio wave is bent so much that it actually returns to Earth. The effect appears to be similar to that of a light beam being reflected from a mirror.

As you can see, the radio wave actually returns to the Earth at some distance from the transmitter. Receiving stations in the area of the refracted signal can receive it. In some cases, if the signal is strong enough and the characteristics of the Earth are right, the radio signal may actually be reflected by the Earth back up to the ionosphere where it is again bent and returned to Earth. Under the right conditions, the radio signals can make several hops, thereby greatly extending the distance of communications. With the optimum frequency, power level, and time of day, communications halfway around the world can easily be achieved. That is why it is easy for you to listen to worldwide radio broadcasts that occur in the SW frequency bands.

VHF, UHF, Microwaves and Millimeter Waves

Radio wave propagation in the frequency range above 30 MHz occurs essentially by direct antenna-to-antenna space waves. This is usually called *line-of-sigh (LOS) communications*. Further, the higher the frequency of the radio wave, the less it is affected by the ionosphere. UHF and microwave signals penetrate the ionosphere, making satellite and long-distance spacecraft communication possible.

$$D = \sqrt{2H_t} + \sqrt{2H_r}$$

D = Line-of-sight distance (miles)
H_t = Height of transmitting antenna
H_r = Height of receiving antenna

If $H_t = 200$ ft and $H_r = 40$ ft,

$$D = \sqrt{2(200)} + \sqrt{2(40)} = \sqrt{400} + \sqrt{80}$$

$$D = 20 + 8.94 = 28.94 \text{ miles}$$

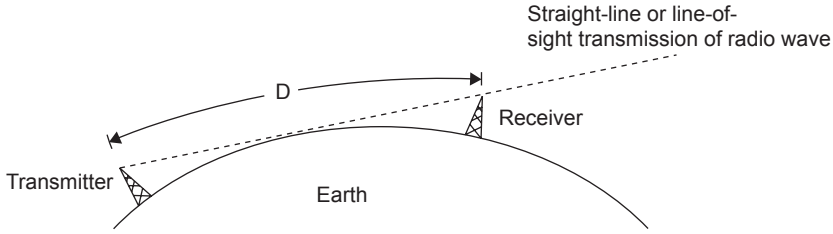


FIGURE 7.6 Line-of-sight (LOS) communications at VHF, UHF, and microwave.

LOS communications means that the transmitting antenna must be able to "see" the receiving antenna. If the distance of the receiving antenna is beyond the curvature of the Earth, the transmitted signal will simply pass over the antenna. To receive the signal, the receiving antenna or transmitting antenna can be increased in height, thereby extending the total range of communications. Fig. 7.6 shows this idea. The simple formula along with it allows you to calculate the maximum LOS communications if you know the height of the receiving and transmitting antennas. That 'is why at VHF, UHF, and microwave frequencies, the height of the antenna is the most critical determining factor in overall communications distance.

MODULATION

A radio wave is a sine wave of voltage that has been converted into electric and magnetic fields by the antenna. The transmitter generates the sine wave and amplifies it to a high power level. The question is: how does the information to be transmitted fit into this?

The information or intelligence to be conveyed is usually a voice signal produced by a microphone. Other forms of intelligence signals include pictures or video and digital (binary) data from a computer. The purpose of the HF sine wave radio signal is to give the intelligence signal a ride. That 'is why the radio signal generated by the transmitter is called the carrier. Modulation is the process by which the information is impressed on or embedded in the carrier. Modulation causes the carrier to be modified by the information signal.

There are three basic forms of modulation used to put information on a carrier: *amplitude modulation* (AM), *frequency modulation* (FM), and *phase modulation* (PM).

Amplitude Modulation

In AM, the voltage or power level of the information signal changes the amplitude of the carrier in proportion (see Fig. 7.7). With no modulation, the AM carrier is transmitted by itself. When the modulating information signal (a sine wave) is applied, the carrier amplitude rises and falls in accordance. The carrier frequency remains constant during AM.

AM is widely used in radio. AM broadcast stations are, of course, amplitude modulated. So are CB radios, aircraft radios, and the video modulation of a TV broadcast transmitter. A special form of AM, known as quadrature amplitude modulation (QAM), is also widely used in modems to transmit digital data over cable or wireless.

Sidebands

The modulation process causes new signals to be generated. These new sine wave signals are called sidebands. Their frequencies are the sum and difference

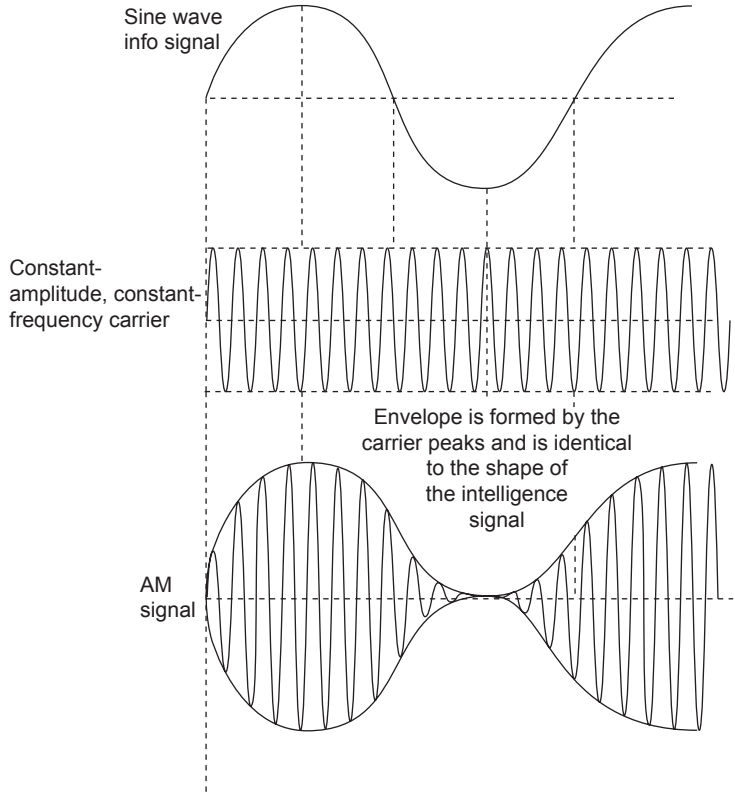
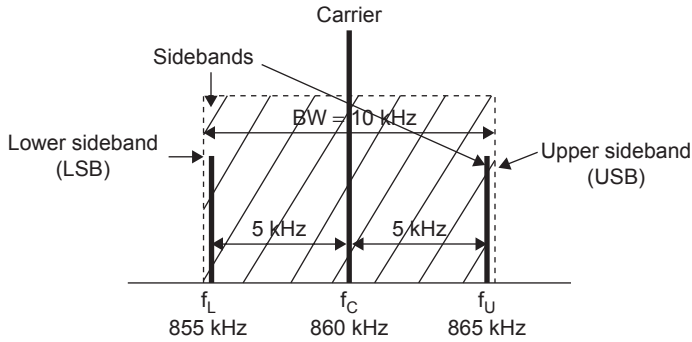


FIGURE 7.7 Amplitude modulation.



f_M = Frequency of modulating signal (5 kHz)
f_C = Carrier frequency (860 kHz)
f_L = Lower sideband frequency
f_U = Upper sideband frequency

$f_L = f_C - f_M = 860 - 5 = 855$ kHz
$f_U = f_C + f_M = 860 + 5 = 865$ kHz

$BW = f_U - f_L = 865 - 855 = 10$ kHz

FIGURE 7.8 Sidebands and bandwidth.

of the carrier and modulating signal frequencies. For example, in an AM radio station, audio frequencies as high as 5 kHz can be transmitted. If a 5-kHz sine wave tone is to be transmitted, the modulation process causes sidebands 5 kHz below and 5 kHz above the carrier to be produced. This is illustrated in Fig. 7.8. For an AM radio station with a carrier frequency of 860 kHz, the lower sideband (LSB) would occur at 860 − 5 = 855 kHz, while the upper sideband (USB) occurs at 860 + 5 = 865 kHz. The carrier and the sidebands combined produce the composite waveform shown at the bottom of Fig. 7.7.

Bandwidth

This brings up the very important concept of bandwidth. Bandwidth refers to a range of frequencies over which a radio signal operates. This is also referred to as a radio channel. As you can see from Fig. 7.8, the AM signal consists of the carrier and the sidebands. Together these signals occupy a bandwidth of 10 kHz. You can figure out the bandwidth of any signal by simply subtracting the LSB frequency from the USB frequency.

$$\text{BW} = \text{USB} - \text{LSB} = 865 - 855 = 10 \text{ kHz}$$

All of the receiver circuits must be set to pass signals in this 10-kHz range to avoid distortion of the signal or lost information.

Single Sideband Modulation

Single sideband (SSB) modulation is a special form of AM in which the carrier and one sideband are suppressed. All of the information to be transmitted such as voice is fully contained in one sideband. This does two things. First, it reduces the required spectrum to one half of that of a normal AM signal thereby saving spectrum space. Second it eliminates the wasteful carrier power and allows more power to be put into the sideband providing more reliable communications. SSB is used in some military applications and is widely used in amateur radio and citizen's band (CB) radios.

Frequency Modulation

In frequency modulation, the carrier amplitude remains constant, but its frequency is changed in accordance with the modulating signal. Specifically, the higher the amplitude of the information signal, the greater the frequency change. The actual carrier frequency deviates above and below the center carrier frequency as the information signal amplitude varies. Fig. 7.9 shows frequency modulation with a sine wave information signal. Note that the carrier frequency gets higher on the positive peaks and lower on the negative peaks of the information signal.

Like AM, FM also produces sidebands. But unlike AM, which produces a single pair of sidebands for each frequency in the modulating signal, the FM process produces an infinite number of pairs of sidebands for each frequency in the information signal. As a result, the bandwidth occupied by an FM signal is enormous. Luckily, the number of sidebands produced can be controlled by

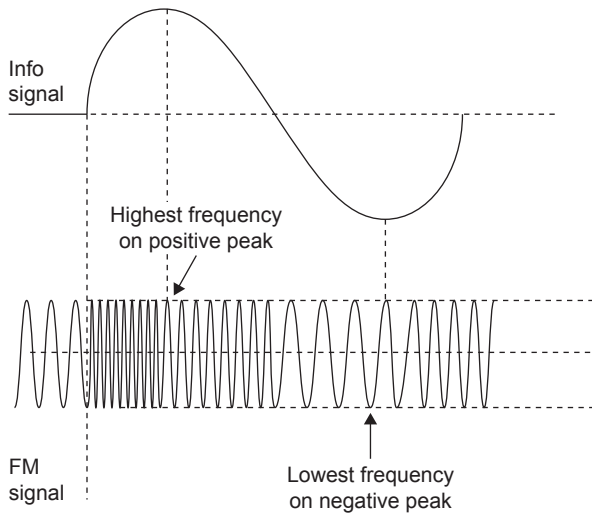


FIGURE 7.9 Frequency modulation.

properly selecting the amount of deviation permitted in the carrier. Small deviations result in fewer sidebands. Further, some of the higher-order sidebands are extremely low in amplitude and, therefore, contribute little to the FM signal. But while the bandwidth of an FM signal can be controlled and established to fit a desired frequency range, it does nevertheless usually take more room in the spectrum than an AM signal.

The primary benefit of FM is that it is less sensitive to noise, which consists of undesirable amplitude variations that get involuntarily added to a signal. Noise is easily eliminated in an FM system where a constant carrier amplitude is used. Some of the most common applications of FM include FM radio broadcasting, and two-way mobile and marine radios.

Phase Modulation

The third type of modulation is PM. Remember that phase shift is a time shift between two sine waves of the same frequency. We can use the information signal to shift the phase of the carrier with respect to the carrier reference. The result of this, however, is a signal that looks virtually the same as an FM signal (Fig. 7.9). PM is usually a little easier to implement electronically than FM, so most so-called FM systems typically use PM instead. Both FM and PM are often referred as types of *angle modulation*.

Digital Modulation

All of the three basic types of modulation, AM, FM, and PM, can also be used to transmit digital or binary data. However, they are usually given different names. AM of a carrier by a binary signal is usually referred to as amplitude shift keying (ASK). This is illustrated in Fig. 7.10A. The binary signal simply shifts the carrier amplitude between two specific levels. A special form of ASK is called on–off keying (OOK). This is illustrated in Fig. 7.10B. Here the binary signal simply turns the carrier on for a binary 1 and off for a binary 0.

Frequency modulation of a carrier by a binary signal is called frequency shift keying (FSK). Here the binary signal shifts the carrier between two discrete frequencies (see Fig. 7.10C).

PM of a carrier by a binary signal is referred to as phase shift keying (PSK). The term binary PSK (BPSK) is also used. The phase of the carrier is changed as the binary signal switches from 0 to 1 or 1 to 0 (see Fig. 7.10D). Phase shift is 180 degrees, which is easily detected at the receiver.

One of the most widely used forms of digital modulation is QAM, which is really a composite of both AM and PSK. The binary signal is converted into a multilevel digital signal that simultaneously modifies both the amplitude and the phase of the signal. QAM is used in digital data transmission in satellites and in modems sending digital data in audio form over telephone lines or cable TV systems. It is also widely used in the newer digital wireless networks. See Chapter 8 for more detail.

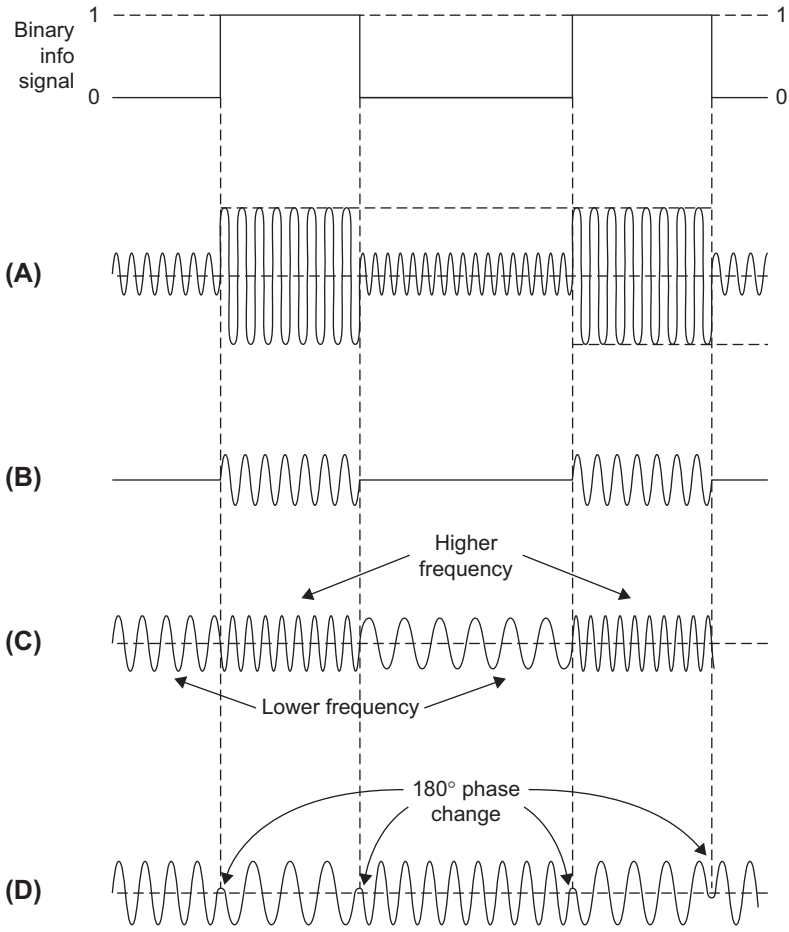


FIGURE 7.10 Types of digital modulation. (A) ASK. (B) OOK. (C) FSK. (D) BPSK.

Because binary signals contain many higher-frequency harmonics, the resulting signals produced by modulation have an enormous bandwidth. Many schemes have been developed to limit the spectrum of the modulating signal and, as a result, to reduce the amount of bandwidth occupied by a binary modulated radio signal.

Spread Spectrum

Spread spectrum (SS) is unusual in that it is not only a form of modulation but also a system for encrypting the information signal for security purposes and for multiplexing multiple signals over a range of frequencies.

SS was originally developed during World War II as a way to prevent the enemy from interpreting radio transmissions. For years the government and

military protected the concepts of SS modulation. However, today it is widely used in radio and telephone communications. Most of the newer cellular telephones are based on this concept, specifically code division multiple access (CDMA) cell phones.

When using SS, the analog information signal is converted into a digital signal before transmission. The digital voice signal is then used to modify the carrier in a special way. The two most common ways of modifying the carrier are referred to as *direct-sequence* (DS) and *frequency-hopping* (FH) *spread spectrum*. In DSSS, the serial digital signal representing the voice is chopped up into random sequences and then used to PSK the carrier. In FHSS, the carrier is rapidly switched from one frequency to another for a short dwell time. The result of SS modulation is that the signal itself is broken up at random, and spectral energy is spread over a very wide frequency range. Because of the random sequences of the coding and FH, such a radio signal is nearly impossible to put back together at a receiver without knowing the code. SS receivers designed to pick up the SS signal know the code and can unscramble the signal and reassemble it into the original modulating information signal.

Orthogonal Frequency Division Multiplex

Orthogonal frequency division multiplex (OFDM) is another widely used modulation technique. OFDM and its usual companion modulation QAM are covered in detail in Chapter 8 on cell phones.

RADIO HARDWARE

All radio communications systems consist of three basic pieces of hardware: *transmitter*, *receiver*, and *antenna*. In some systems, the transmitter and receiver are packaged and used separately, while in others they are combined into a single package and called a *transceiver*.

Transmitters

The radio signal is produced by the transmitter. A general block diagram that applies to virtually every transmitter is shown in Fig. 7.11. The radio signal is generated at a low power level by a frequency synthesizer. This uses a phase-locked loop (PLL) with a crystal (XTAL) oscillator reference. A variable-frequency divider is used to set the frequency of operation. The FCC is really fussy about the frequency at which transmitters work and, therefore, the frequency must be precisely set and extremely stable. A quartz crystal reference oscillator is normally used to achieve this objective.

The low-level signal produced by the voltage-controlled oscillator (VCO) is then amplified by one or more driver amplifiers to boost the power level. Next, the microphone signal is fed to the modulator. The modulator changes the

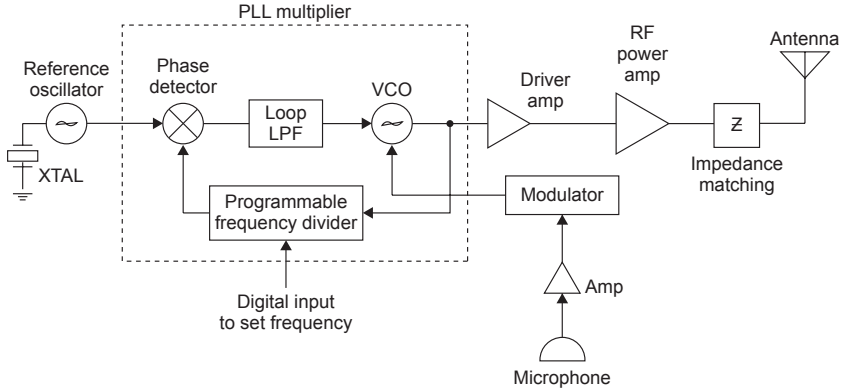


FIGURE 7.11 Radio transmitter.

frequency or phase of the RF signal in accordance with the voice, digital data, or other information to be transmitted. That signal is applied to the PLL VCO.

The modulated signal is sent to additional RF power amplifiers, usually referred to as *drivers*. Each succeeding stage boosts the signal power by a specific amount. A final RF power amplifier produces the desired amount of output power. From there, impedance (Z) matching circuits are used to match the high-power amplifier (HPA) to the antenna for maximum power radiation.

The physical realization of the transmitter can vary all the way from a single integrated circuit chip, the size of a postage stamp to something that can fill up a moderately large building. The size depends on the operating frequency and the amount of output power desired. Very-low-power, HF radio transmitters for garage door openers and remote keyless entry systems on cars are fully self-contained within a single integrated circuit. High-power radio broadcast transmitters at LFs may fill a small room. The higher the power and the lower the frequency, the larger the transmitter.

Receivers

The job of the receiver is to translate the weak radio signal picked up by the antenna into an output that fully recovers the originally transmitted information. By the time the radio signal reaches the receiving antenna, it is extremely weak and, therefore, the primary job of the receiver is to boost the signal level. Therefore, the receiver consists mainly of a series of amplifiers that increase the level of the small signal to a point where the original information can be recovered.

The amount of amplification provided by a receiver determines its *sensitivity*. Another job of the receiver is to provide selectivity so that the desired signal can be picked out of the thousands of signals being transmitted simultaneously by other transmitters. The receiver's job is to select just the desired one and to reject all of the others. This is what we refer to as the *selectivity* of the receiver.

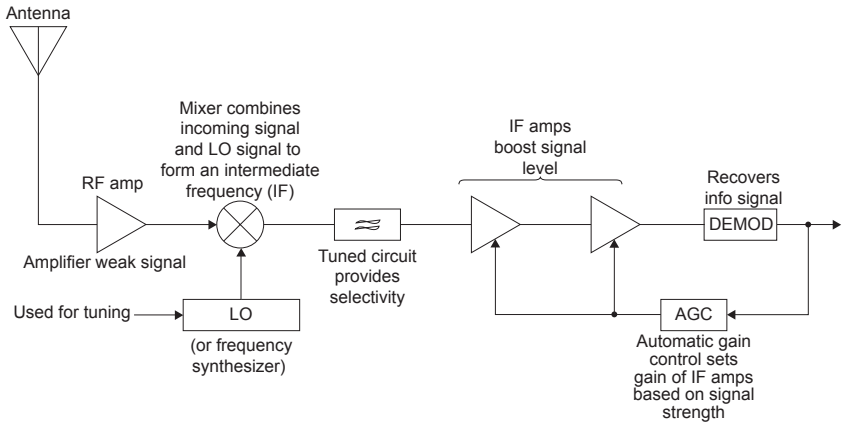

Antenna
Mixer combines incoming signal and LO signal to form an intermediate frequency (IF)
RF amp
IF amps boost signal level
Recovers info signal
DEMOD
Amplifier weak signal
Tuned circuit provides selectivity
Used for tuning
LO
(or frequency synthesizer)
AGC
Automatic gain control sets gain of IF amps based on signal strength

FIGURE 7.12 Superheterodyne receiver. *LO*, local oscillator.

A third function of the receiver is to recover the original information. A circuit called a *demodulator* removes the voice, video, or digital data from the carrier. Finally, output amplifiers reproduce the signal as desired, such as a voice signal in a speaker.

Fig. 7.12 is a block diagram of a superheterodyne receiver. The incoming signal is usually amplified by an *RF input amplifier* often called a *low-noise amplifier* (LNA) and then fed to a circuit called a *mixer*. The mixer is a frequency-translation circuit that converts the incoming signal, regardless of its frequency, along with its modulation to a lower intermediate frequency (IF). This allows the receiver to use a fixed-frequency amplifier system where most of the gain and selectivity of the receiver is achieved. The mixer takes the input signal and mixes it with a HF sine wave signal generated internally in the receiver by what is called a local oscillator (LO). The LO is usually a frequency synthesizer. The result of the mixing is output signals that are the sum and difference frequencies of the input and oscillator signals. The IF amplifier is normally tuned to select only the difference frequency. Tuning is accomplished by changing the LO frequency. The LO in most channelized receivers is some type of PLL frequency synthesizer.

The IF amplifier boosts the signal level considerably. Its selectivity ensures that signals whose frequencies are above or below the desired signal are effectively eliminated. The IF amplifier also has a built-in feedback control circuit that automatically adjusts its gain to the level of the incoming signal. This feature is called *automatic gain control* (AGC). AGC permits the receiver to pick up both strong local signals and very weak distant signals. When very strong signals are received, the AGC automatically reduces the gain of the IF amplifier to minimize circuit overload and signal distortion. When very weak signals are received, the AGC adjusts the gain of the IF amplifier for higher amplification.

The *demodulator circuit*, sometimes called the *detector*, follows the IF amplifier. It removes the carrier and recovers the desired information signal. From there, additional processing takes place to either boost the signal level or to shape it before it appears at the output.

Most receivers that we are familiar with have a speaker as the primary output. But there are exceptions, such as the picture tube in a TV set or the motor in a garage door opener. The receiver may also put out digital data that goes straight to a computer.

Transceivers

Most communications systems use both a transmitter and a receiver. In two-way radio, both send and receive capability is needed at both ends of the communications channel. Therefore, the receiver and transmitter are packaged together in the same housing to create a transceiver. Small portable transceivers are called handhelds, walkie-talkies, or cellular telephones.

The transmitters and receivers are typically the same as those described earlier. However, in some cases, the transmitter and receiver may share circuits. They virtually always share the antenna and a common power supply like a battery. In some cases, a single-frequency synthesizer may generate both the receiver LO signal as well as the transmitter carrier.

ISM Band Transceiver

The ISM band refers to specific frequencies set aside for wireless industrial, scientific, and medical (ISM) applications. The most common frequencies in the United States are 315, 433, and 915 MHz. The frequency 868 MHz is widely used in Europe. These unlicensed frequencies are used for simple monitor and control applications using low-speed digital data over short ranges. Some common examples are garage door openers, remote keyless entry on cars, remote thermometers, tire pressure gauges, security and fire alarms, home automation, and any telemetry or remote control application. The radios used for this are typically single ICs to which an antenna, a battery, a housing, and the input data are added. The devices are available as a receiver, a transmitter, or a complete transceiver. Fig. 7.13 is a block diagram of a typical transceiver.

The transmitter section uses an external crystal to serve as the reference to an internal PLL frequency synthesizer to set the frequency. The PLL actually multiplies the crystal frequency by some N value to get the desired output. If the crystal frequency is 6.77 MHz and the divide ratio is 64, the output would be 433.28 MHz. The serial digital data input coming from a sensor, an analog-to-digital converter (ADC), or a computer frequency modulates the crystal oscillator to create the FSK signal. A power amplifier after the transmit VCO boosts the power up into the 1- to 100-mW range. The output goes to the antenna. A transmit/receive switch allows the antenna to be shared in a half-duplex system.

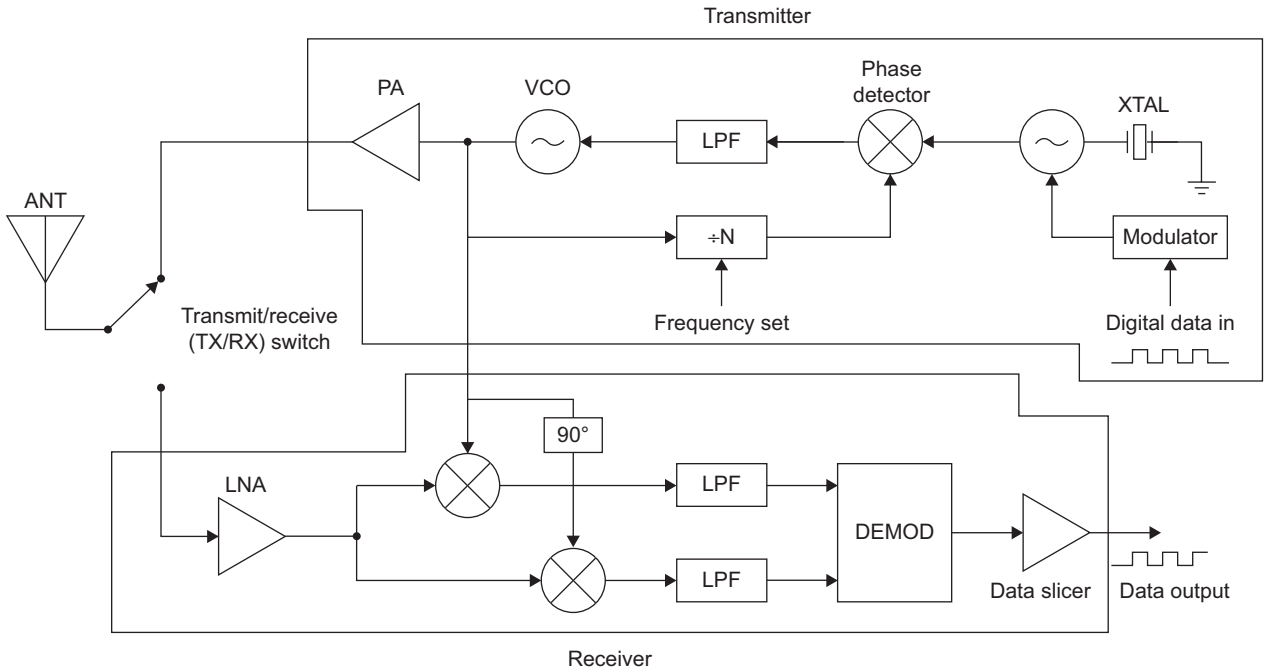


FIGURE 7.13 Single-chip UHF transceiver for low-speed, short-range digital data transmissions.

The receiver is a special version of a superheterodyne. The input signal from the antenna is boosted in amplitude by the LNA and applied to the mixers. The LO is set to the incoming signal frequency (also the transmit frequency), so the mixers generate a difference of zero. This is called *direct conversion* or *zero IF*. Two mixers are used and the LO is shifted 90 degrees in phase between the two. This gives two zero IF outputs that are filtered. Zero IF does not mean a nonexistent output signal. It just means that the FSK signal is recovered directly at its data rate. The I and Q signals are 90 degrees out of phase, and this allows the digital data to be more easily demodulated. A data slicer, a circuit like a comparator, is used to shape the signal into a clean binary bitstream. With this kind of radio, the range is limited. It may be only a few feet or up to a mile or so depending on the antenna, environment, or application.

ANTENNAS

The antenna takes the voltage and current produced by the transmitter and converts it into the electromagnetic wave we know as a radio wave. At the receiver, the antenna converts the electromagnetic field back into a voltage we know as the radio signal. The radio waves pass over the receiving antenna, inducing a voltage that causes current to flow in the receiver.

Antennas can have an amazing variety of shapes. Essentially an antenna or aerial is some arrangement of electrical conductors whose size and length are critical. For optimum operation, the antenna length must be related to the wavelength (λ) of the signal. Common antenna sizes are one-quarter (λ/4) and one-half (λ/2) wavelength at the operating frequency. The higher the frequency, the shorter the wavelength and thus the smaller the antenna. For example, one wavelength at 150 MHz, a popular two-way radio frequency range measures 2 m. A half wavelength is 1 m and a quarter wavelength is 0.5 m. Since 1 m is 39.37 in., a half wavelength is 19.68 in. At 900 MHz, the frequency range of cell phones, one wavelength is 0.3333 m. A quarter wavelength antenna would be 0.3333/4 = 0.08333 m or 3.28 in.

Ground-Plane Antenna

Antennas can be anywhere from a long horizontal copper wire to a vertical steel or aluminum tower several hundred feet tall. Or it may be an array of short conductors like those in a TV antenna. One of the most common antennas is a short quarter wavelength vertical that is widely used in mobile radios, cell phones, and other handheld units (see Fig. 7.14). The quarter-wave or ground-plane antenna, as it is sometimes called, radiates equally well in all directions, making it omnidirectional. We say that its radiation or reception pattern is a circle.

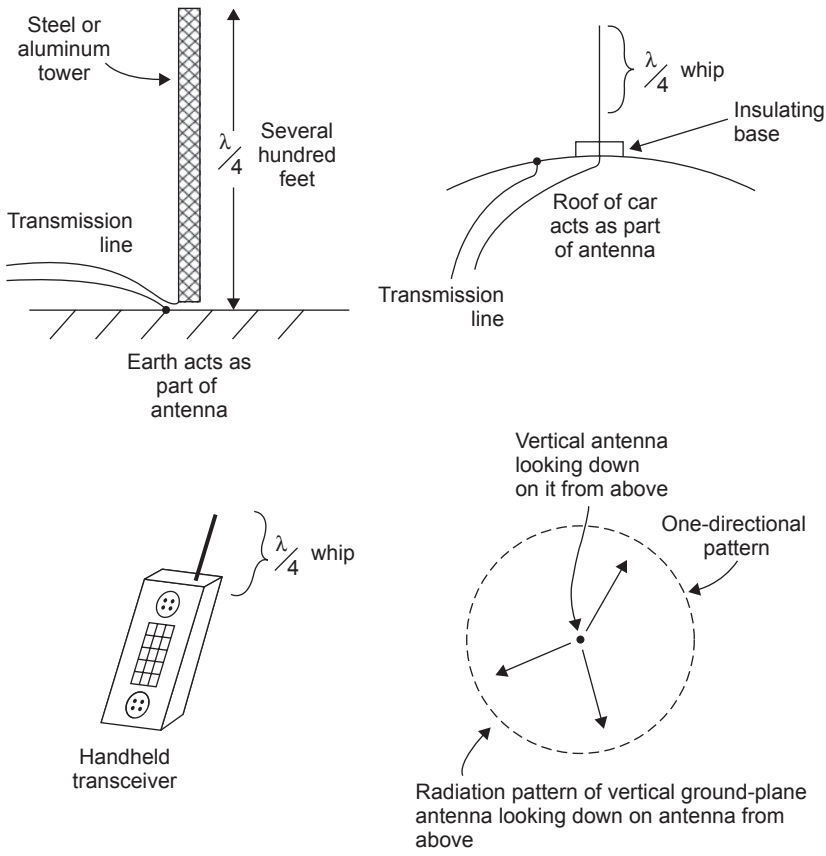

Steel or aluminum tower
λ/4
Several hundred feet
Transmission line
Earth acts as part of antenna
λ/4 whip
Insulating base
Roof of car acts as part of antenna
Transmission line
λ/4 whip
Handheld transceiver
Vertical antenna looking down on it from above
One-directional pattern
Radiation pattern of vertical ground-plane antenna looking down on antenna from above

FIGURE 7.14 Quarter-wave ground-plane antenna.

Dipole

Another common antenna type is the dipole, which is one-half wavelength long and usually mounted horizontally. Fig. 7.15A shows an example. Its radiation or reception pattern in Fig. 7.15B is a figure eight. The greatest radiation or strongest reception occurs at a right angle to the dipole element itself.

Yagi

A variation of the dipole is the Yagi, a multielement antenna based on the dipole shown in Fig. 7.16. To the dipole is added a reflector element that is slightly longer than one-half wavelength, and one or more director elements that are progressively shorter than the dipole. The directors and reflector make the Yagi highly directional. The extra elements, called *parasitic elements*, concentrate and aim the beam of radiation over a narrow range. At the transmitter, this has the effect of increasing the transmitted power,

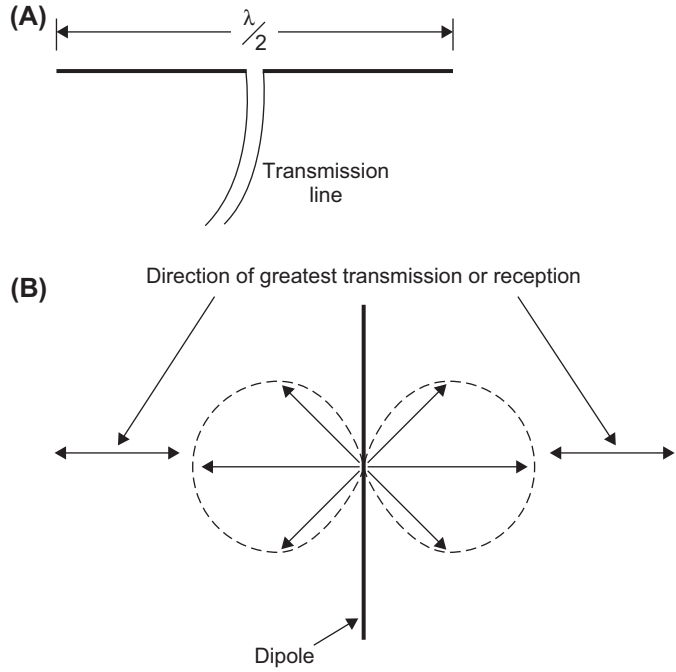


FIGURE 7.15 Dipole antenna. (A) Dipole and (B) horizontal radiation pattern.

making the signal stronger at the receiver as if the transmitter power had been increased. A similar gain effect occurs at the receiver.

Other Antennas

There are many other antenna variations. Antennas formed with copper patterns on a printed circuit board (PCB) are widely used. One example is the *patch antenna* (see Fig. 7.17). It is simply a square area of copper about one-half wavelength on a side made on a PCB. Another is the *loop antenna* that is just a loop of copper on the PCB. A popular cell phone antenna is the inverted F, which is an F-shaped pattern on the PCB. Antennas also come as components. For microwave frequencies, there are special antennas made on a ceramic base that are small and can be soldered to a PCB.

Transmission Lines

The antenna is usually connected to the transmitter or receiver by way of a coaxial cable (see Fig. 7.18). It consists of a copper center conductor surrounded by an insulator, such as Teflon. Around that is a shielded copper braid or foil. The whole thing is covered with a plastic insulator. Coaxial

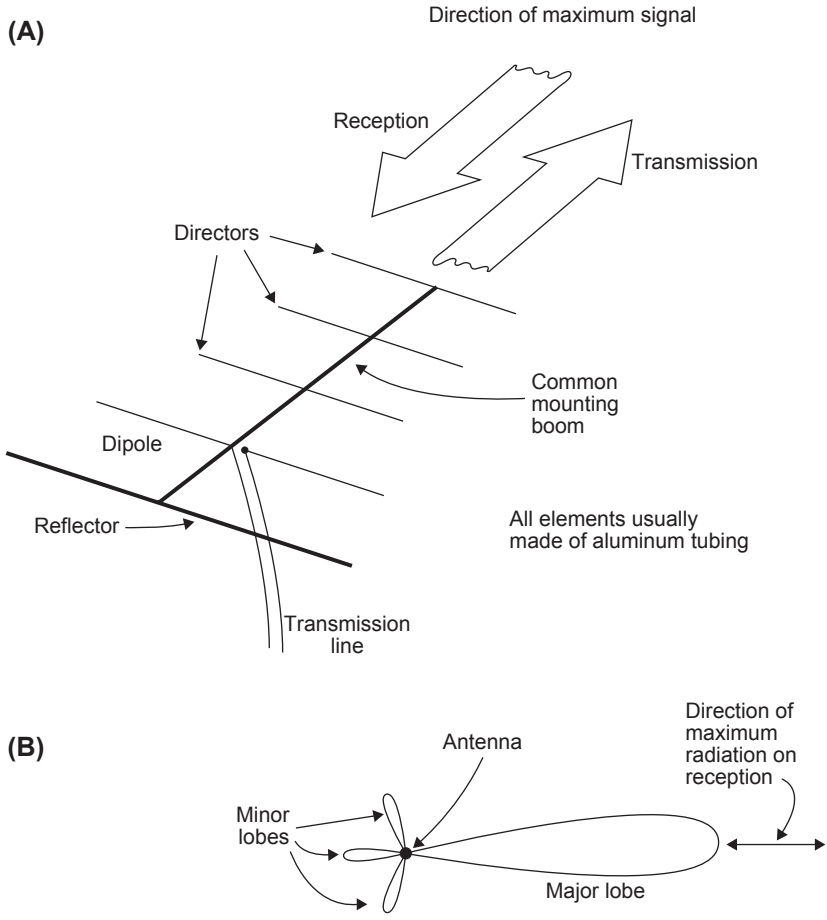


FIGURE 7.16 Yagi antenna. (A) Yagi and (B) radiation pattern.

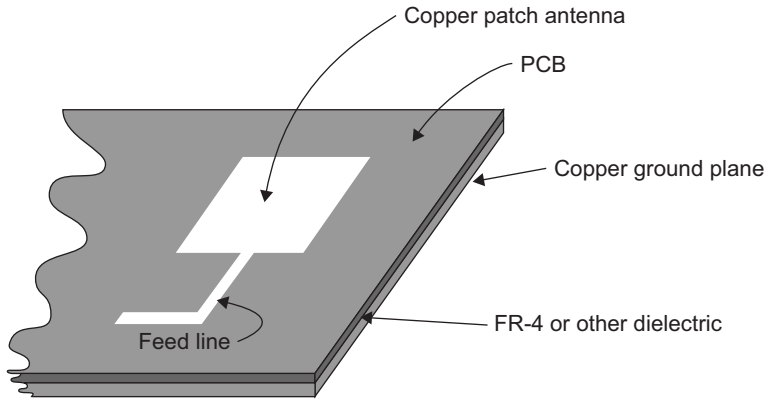


FIGURE 7.17 Printed circuit board (PCB) patch antenna.

cable is the most commonly used transmission line to connect the equipment to the antenna. It provides an efficient method of transferring the voltages and currents to and from the antenna while providing a certain amount of shielding from noise. For PCB antennas, the transmission line is just a short pair of copper lines from the transceiver IC to the antenna. The transmission line impedance most commonly used in RF systems is 50 Ω. Some systems such as cable TV use 75-Ω cable.

Microwave Antennas and Waveguides

Antennas used at microwave frequencies are quite different from those used at the lower frequencies. Perhaps the most common is the *horn antenna*. It looks like the flared end of a musical horn, only most of them have an opening or aperture that is rectangular rather than round.

As seen in Fig. 7.19, the horn is directional and has gain. The microwave energy is fed to the horn by a transmission line. Coax can be used for the lower microwave frequencies, but at the higher microwave frequencies, coaxial cable loss is too high for long runs. A high percentage of the signal power is lost in the coax cable itself. This problem is overcome by using a waveguide. A waveguide is nothing more than a hollow copper pipe, usually with a rectangular cross section through which the microwave energy passes from transmitter to antenna or from antenna to receiver.

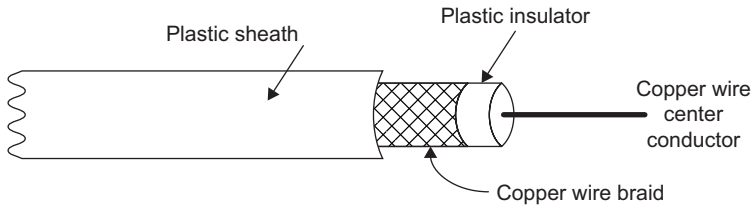


FIGURE 7.18 Coaxial cable transmission line.

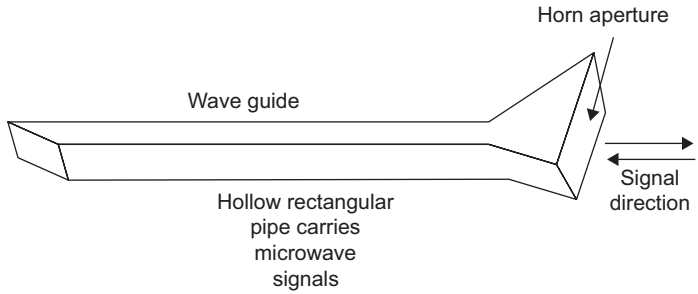


FIGURE 7.19 Microwave horn antenna fed by waveguide transmission line.

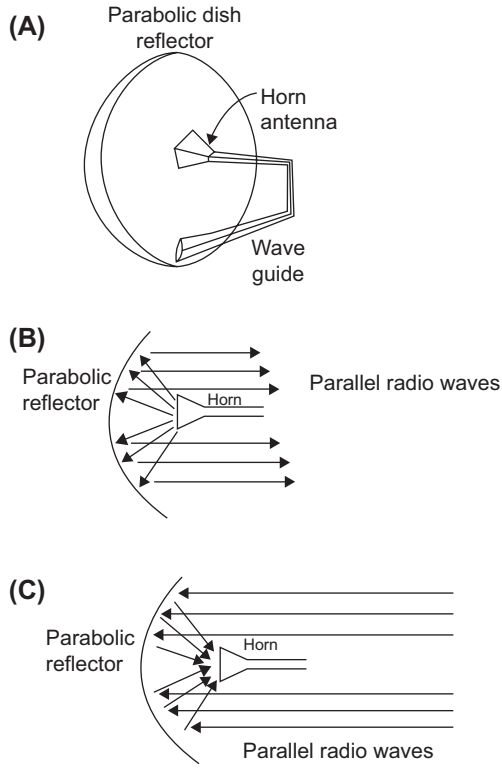


FIGURE 7.20 How a parabolic dish works. (A) Parabolic dish with horn, (B) transmission, and (C) reception.

The most effective and widely used microwave antenna is the parabolic dish (see Fig. 7.20). This is usually a horn antenna combined with a reflector shaped like a dish. Its shape is a mathematical parabola. Signals transmitted by the horn are reflected forward by the parabolic dish shaping the radio waves into a very narrow beam. Received energy is reflected by the dish into the horn antenna. The highly directional nature of the dish gives it a very narrow beamwidth and enormous gain. These are widely used in satellite TV and radar.

TWO-WAY RADIO

Two-way radio communications between individuals are by far the most widespread use of radio. And there are many forms of it. You have seen such radio communications as they take place and you have no doubt engaged in some form of it yourself. In any case, this section takes a look at some of the diverse uses of such two-way communications.

Most two-way radios operate in the VHF and UHF bands. The simplest two-way radios operate on multiple frequencies usually selected by a frequency

synthesizer. Virtually all two-way radio communications are half duplex, meaning that one party transmits while the other receives. Transmit and receive operations are controlled with a push-to-talk switch on the side of the microphone or handheld unit.

Aircraft

All airplanes from the smallest single-prop planes to the largest jumbo superjets use two-way radio to communicate with airport towers and the major air traffic management centers across the country. Two-way radio is absolutely essential to the safety of any flight.

Most aircraft radios are transmitters installed in front of the pilot or copilot. They usually operate in the 108- to 135-MHz band and use AM. Specific channels are assigned for different regions and for different communications functions. The pilot or copilot uses front panel switches to select the desired communications frequency. Handheld microphones with a push-to-talk switch are the most commonly used input devices, but other forms of microphones such as throat mikes or microphones attached to headsets are also widely used. Most transceivers operate at very low power, and transmission distances are considerable. The height of the airplane gives the radio transceiver an enormous transmission range even with low power at VHF frequencies.

Citizens Band

You have no doubt heard of CB radio and perhaps even used one yourself. Anyone can buy and use a CB radio for two-way communications. The FCC has allocated 40 frequencies or channels in the 27-MHz frequency range for CB operation. The maximum transmission power is restricted to 5 W, although some handheld units use less. Modulation is AM but SSB is used in some units.

Citizens band radio has enjoyed wide popularity with individuals and sportsmen as well as truckers. While the advent of the cellular telephone has reduced the number of individuals using CB radio, it is still widely used. The primary limitation of most CB radios is the antenna. Since CB radios operate in the 27-MHz range, the required minimum antenna length is approximately 9 ft. This can be shrunk somewhat by the use of coils attached to the antenna, but effectiveness is reduced. A CB radio antenna of 5 or 6 ft is common and certainly manageable on a car, truck, or boat. In handheld transceivers, any antenna longer than about 18 in. is a nuisance.

A 27-MHz frequency allocation of CB radio also gives it some peculiar transmission characteristics. While communications is reliable over short distances of up to several miles, at certain times of the day or evening, worldwide communication is also possible. This is probably more a disadvantage than an advantage, primarily because interference can be received from stations literally anywhere in the world.

Amateur Radio

Amateur or ham radio is a hobby. Technically knowledgeable individuals are licensed by the FCC to use selected frequency bands across the spectrum for personal communications. Hams use FM or SSB voice as well as CW (continuous wave) or Morse code transmissions. Hams are also beginning to use digital modes such as PSK. Hams talk to one another about their equipment, the weather, and other common matters. Communication is worldwide and helps to promote good international relationships. Hams have proven their worth with emergency communications during hurricanes and other natural disasters. Hams frequently design, build, and experiment with their own equipment, although many hams prefer commercially manufactured radios. Hams also experiment with digital radios, satellites, and TV.

Family Radio

Family radio is another radio service recently instituted by the FCC for the purpose of short-range personal communications. It supplements CB radio in a wide range of personal communications needs. Because of a different frequency allocation, family radios are smaller, more portable, and have more reliable communications over distances of several miles.

All family radios are handhelds using FM and operating in the 462 and 467 MHz range. Only several frequencies in the 462/467 MHz band are allocated to the Family Radio Service (FRS). While many users will share these frequencies, the short communication distances minimize interference between stations using the same frequency. The transceivers are restricted to 0.5 W in power. At a frequency of 462 MHz, a quarter-wave whip antenna is only about 6 in. long. Communications are extremely reliable up to 1 mile and even farther if transmission takes place outdoors.

You can use family radios in a variety of ways. They are particularly handy when you are camping, hiking, or doing other outdoor activities. Many families use them in shopping malls and even around the house to keep in touch. They are great on farms and ranches and for communications between two nearby cars.

Marine

The very first application of two-way radio in the world was on ships at sea. Ships were always in danger without any form of communication. If a ship was disabled or began sinking, no one would know for a long period of time or maybe never. With a two-way radio or even a one-way radio on a ship, the operator could communicate with a shore-based radio station to signal danger with the familiar SOS.

Today, a radio is a necessity on virtually every boat and ship. While small boats are not required to carry radios, most larger boats are. And what seaman would be without a radio for safety reasons?

Marine radios have operated on a wide range of frequencies over the years. Ocean-going liners have operated on SW frequencies so that long-distance communications are possible. Ships also operate on lower frequencies for exchanging messages and at the higher frequency for reliable communications near land and in port.

The typical marine radio for communicating near ports is a transceiver of 25–40 W of power operating with frequency modulation in the 150- to 170-MHz range. Most of these units transmit on multiple frequencies, making it always possible to find a clear channel. Channel 16, operating on a frequency of 156.8 MHz, is used for emergency calls. This frequency is typically monitored by other boaters and always by the Coast Guard.

Land Mobile Radio

Land mobile radio refers to two-way radios mounted in cars and trucks. These are widely used by police, fire, and other public safety and civil services. They are also widely used by taxis, buses, trains, and by companies using fleets of cars or trucks for convenient communications. The typical unit is mounted in the vehicle and provides relatively high power in the 25- to 50-W range. Most communications take place in the 150- to 170-MHz range. Other mobile radio frequency ranges are 450–470 MHz. Many of the radios today are handheld types.

SATELLITES

A satellite is a space station that is designed to orbit the Earth and provide a remote radio signal relaying station for the purpose of extending the range of communications worldwide. See Fig. 7.21. Such communications satellites contain both a receiver and transmitter that operate simultaneously. The receiver

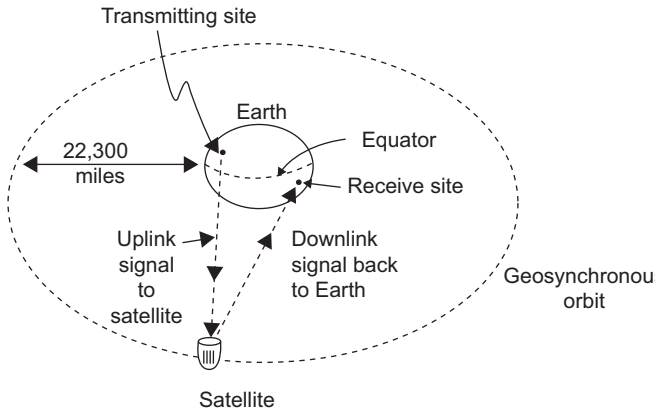


FIGURE 7.21 Concept of communications satellite.

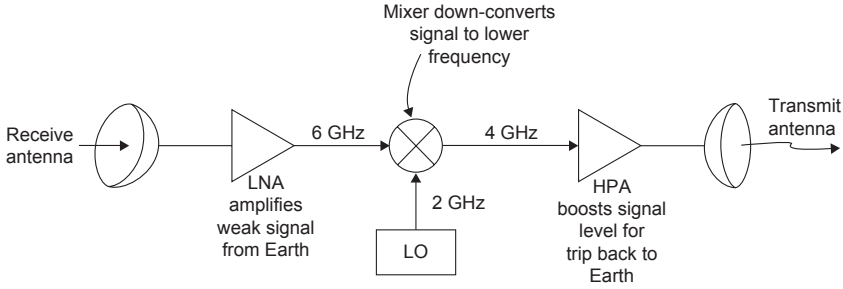


FIGURE 7.22 Satellite transponder. *LO*, local oscillator.

picks up signals from the Earth on one frequency and retransmits them simultaneously on another frequency. In this way, the transmitter and receiver in the satellite do not interfere with one another.

Most communications satellites are geosynchronous. These are satellites positioned to orbit directly around the Earth's equator at a distance of 22,300 miles from Earth. When located in this position, the satellite rotates in exact synchronization with the Earth's rotation; thus, the term *geosynchronous*. Because the satellite and the Earth are rotating together, it appears as though the satellite is stationary overhead to an observer on Earth. With the satellite in a fixed position with respect to the Earth, the satellite becomes a near-perfect radio repeater station.

Fig. 7.22 shows a general block diagram of a satellite. The communications part of a satellite consists of a combined receiver and transmitter called a transponder. Satellites operate in the microwave region. The C band from 4 to 6 GHz and the K_u band from 11 to 18 GHz are the most popular operating ranges. A LNA picks up the very small 6 GHz uplink signal from Earth. It is mixed with a 2-GHz LO signal and downconverted to a 4-GHz downlink signal, which is then amplified by an HPA and retransmitted back to Earth. Most satellites contain many transponders with wide bandwidth capable of handling many signals simultaneously.

The satellite power source is batteries combined with a system of solar cells. The solar cells convert light from the Sun into electrical energy that is used to recharge the batteries. This system gives the satellite long life in space.

Communications satellites are used primarily in long-distance telephone communications and for distribution of TV signals. Some satellites are used for navigation, a good example being the GPS widely used by the military and commercial organizations. It is also widely used by individuals as they find their way with personal navigation devices like those from Garmin and Tom Tom. Many of the newer cars and trucks have built-in GPS navigation systems with maps using an LCD screen. The GPS system uses 26–31 satellites about 10,800 miles above the Earth orbiting in overlapping patterns so that at least three of four are "visible" by wireless at any point on the Earth.

Other satellites are used for surveillance. Spy satellites only 102 miles high pick up radio signals as well as IR images and photographs. Weather satellites monitor cloud formations and movements. There are also several satellite telephone networks with low-Earth-orbit satellites to permit communications to/from any point on the planet.

RADIO TELESCOPES

Observation of the planets and stars is usually done with an optical telescope. However, in 1932, researchers discovered that distant stars or suns emitted radio waves. All stars, like our Sun, emit radio frequencies. Most of this energy occurs in the microwave region at 1.4218 GHz. This is the frequency of ionized hydrogen. By building a highly sensitive radio receiver and coupling it to a large highly directional radio antenna, it is possible to plot the position of distant stars just as effectively as an optical telescope. Radio telescopes are, in fact, even more effective in that they can more easily detect distant stars that cannot be seen even by the best optical telescopes.

Radio astronomy observatories consist of an enormous parabolic dish antenna usually 60–250 ft in diameter, which can be rotated and tilted so that it scans the skies. An array of multiple smaller dishes can also be used as in the SETI (search for extraterrestrial intelligence) project in New Mexico. The antennas are coupled to one or more very sensitive radio receivers. These receivers have very high gain so that they can sufficiently amplify very small signals received from stars that are many light years away. Often special cooling systems are used to reduce the temperature of the receiver front end to minimize noise, thereby permitting even weaker signals to be received. One of the largest radio telescopes is a curved dish reflector built of screen mesh 1000 ft in diameter. The dish is built into the valley between adjacent mountains near Arecibo, Puerto Rico. The horn antenna is moveable on a long cable so it can be positioned to see any part of the sky. The world's largest radio telescope is in China.

Wireless Everything

It seems like everything is going wireless these days, such as cordless telephones, wireless local area networks, and your TV remote control. But wireless has always been around just not by that name. Most radio applications are old and well known. A few examples you may have encountered follow.

Garage door opener. A tiny transmitter in your car transmits a binary coded message to the receiver in your garage hooked up to the door motor.

Remote keyless entry. A miniature transmitter on your key ring transmits a signal to a receiver in your car that opens the door locks. Some even turn on lights and start your car from 10 to 30 ft away.

Wireless data acquisition. Remote transmitters are set up with solar batteries at remote sites to gather data from sensors and transmit it back to a collection

Continued

Wireless Everything—cont'd

center. A good example is electric, gas, and water utilities that use such systems to monitor critical conditions at remote sites and transmit the data back to a central monitoring facility where decisions can be made. Home wireless thermometers are very common.

Radio control of models. This is very common in toy cars, model airplanes, and boats.

Drones. Military, commercial, and recreational drones or unmanned aerial vehicles are all wirelessly controlled and that includes a wireless link for the video usually deployed.

RFID. Ultraminiature radios are being embedded in shipping labels, cars, and other objects for identification purposes. The units transmit their unique ID code when scanned by a nearby receiver.

HD radio. This is digital radio broadcasting in the United States. Most US AM and FM stations now transmit a digital version of their signals on the same frequencies as their analog transmissions. They use a form of digital modulation called OFDM (see Chapter 8). It produces greater frequency response than the regular analog broadcasts, making AM sound more like FM and FM sound more like a CD. A special radio is needed to receive it. The digital technology makes noise and fading less of a problem. And it permits each station to add several additional channels thanks to the multiplexing capabilities of the HD technology.

Security tags. The plastic tags clipped on new clothes to prevent their being stolen contain a tiny antenna and electronic circuit that make their presence known at a nearby transmitter/receiver unit.

Surveillance and bugging, or secret monitoring or electronic spying. This is not just something you see in the movies or on TV. It is more widely used in private investigation, police work, and industrial espionage than you may think. Scary! Face it, wireless is truly everywhere.

Project 7.1

Investigate HD Radio

HD radio is digital radio in the United States that shares the same frequencies as the regular AM and FM bands. You can buy stand-alone HD receivers, and some stereo receivers include it. HD radio is also available in some cars. To learn more about this technology, go to the website of the developer iBiquity or www.ibiquity.com. Also try a Google/Bing/Yahoo search on HD radio.

Project 7.2

Become Familiar With ISM Radio

ISM radio is the term used to refer to short-range data radios used in the FCC's unlicensed spectrum designated for industrial–scientific–medical (ISM) applications. Got to the FCC website www.fcc.gov and find the most commonly used ISM frequencies of operation in Parts 15 and 18 of the rules and regulations. Do a general search of ISM to determine some common applications.

Project 7.3

Radar

Radar (radio detection and ranging) is a type of wireless. It has many uses, mainly military but also commercial and civilian. Marine and aircraft navigation are key applications. Police radar is widely used. Radar is also showing up in automobiles as detectors of distance between vehicles for automatic braking. Radar plays a major role in advanced driver assistance systems (ADAS) now being included in most new vehicles and in the forthcoming self-driving cars and trucks. You may wish to learn more about this technology. Do a search on radar.

Project 7.4

Shortwave Radio

Buy a low-cost SW radio and experience listening to international broadcasts and amateur radio operation.

Project 7.5

Experience Citizens Band or Family Radio Service

Go to your local electronic store and buy a pair of FRS walkie-talkies. Then test them to determine maximum range. As an alternative, buy a CB radio and listen to what is going on with the truckers or other locals.

Project 7.6

Experiment with a Short-Range Radio

This project lets you build a short-range radio system using ISM band transmitter (TX) and receiver (RX) modules. The modules are from Radiometrix and available from distributor Lemos. The US modules operate in the ISM band on a frequency of 914.5 MHz and the European modules operate on 869.85 MHz. The modulation is FSK, and data rates to 64 kbps are possible. The project will show how a digital signal can remotely flash an LED or control a relay. Use the following procedure.

- Go to the Radiometrix website and print out the data sheets and any application notes for the TX3A transmitter and the RX3A receiver: www.radiometrix.com. The modules are designed for PCB mounting but also plug easily into a standard breadboarding socket. Read the data sheets.
- Mount the transmitter and receiver on separate breadboarding sockets so that you can space them from one another.
- Provide power to each module separately. The modules will operate from any DC supply in the 2.2–16 V range. Use battery power for portability. You can use your 6 V AA supply or a 9 V battery.
- Wire the modules according to the circuit in Fig. 7.23. The 555 timer oscillator will supply the repeating square wave of data to the TX3A. The RX3A receiver output will drive a transistor switch to turn the LED on and off.

Continued

Project 7.6—cont'd

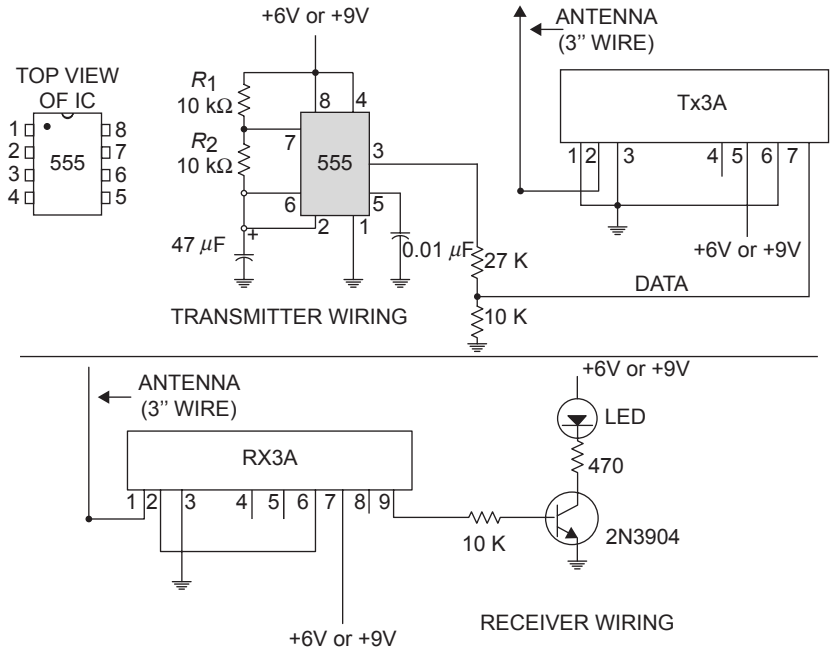


FIGURE 7.23 Wiring details for the ISM band short-range radio experiment.

- For antennas use a 3 in. piece of #22 hook up wire. Just plug one end of the antenna wire into the transmitter RF OUT output on pin 2. The receiver wire antenna should be connected to the RF IN connection on pin 1. Orient the antenna wires vertically.
- Double-check your wiring before applying power to both units.
- Apply power. You should immediately see the LED flashing. This confirms that the wireless link has been established.
- Experiment with transmission range. Move the units as far apart as possible and determine where the connection fails.
- Disconnect power.
- Examine the circuit in Fig. 7.23. You could replace the 555 timer with a push-button and the LED with a relay to perform some remote control function. Other scenarios are possible.

Chapter 8

Cell Phones

It Is Now Possible to Do Anything Wirelessly: Talk, Text, Email, Web Browse, Games, Whatever

In this Chapter:

- How the cellular system works.
- Cell phone radio technologies.
- Digital modulation and access schemes.
- Cell phone data capabilities.
- Smartphones, 4G, LTE, 5G, MIMO, and location technology.

INTRODUCTION

The cell phone is one of the coolest, most useful, and convenient electronic devices of all time. It also happens to be one of the most complex technically, not only internally but also because it is part of the largest communications network in the universe, the telephone system. The reason for a separate chapter on this topic is not only because of the advanced wireless technology involved, but also its importance to all of us personally and to the national economy. Since practically everyone has a cell phone today, it plays a huge role in our lives. And for you techies out there, it is worthwhile knowing a bit of the details of how phone calls work, how text messages get sent, and how you can now access the Internet via your cell phone.

CAN YOU HEAR ME NOW?

We have all said that before. Why? For one simple reason: cell phones are two-way radios with all the usual faults. The cell phone industry usually refers to itself as the wireless industry, but it is all the same thing—radio. Your cell phone contains a *transmitter* and a *receiver* that collectively are called a *transceiver*. You will also hear them called *handsets*. People in the industry also call them *mobile terminals*. The most common designation of a cell phone is *smartphone*. It is much more than just a two-way radio. In fact the smartphones of today

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00008-4
Copyright © 2018 Elsevier Inc. All rights reserved.

contain another three to five radios. In addition, smartphones have been characterized as powerful handheld computers with multiple input/output radios. This later designation may be the most accurate.

Because cell phones have to be so small to be practical, they are limited in the amount of power they can transmit and the type of antenna that is practical. Battery drain is a major factor in cell phone design, as you want to get as much talk time as you can on a battery charge. But by limiting the transmit power, you automatically minimize the distance over which the unit will transmit. In any case, communications range is related to power as well as antenna type and orientation. And the typical range of a cell phone is a mile or so, depending on conditions. Take a look at the sidebar to review some of the facts about wireless and radio covered in Chapter 7.

Factors Affecting Range and Reliability to Radio Transmission

Range—The greater the distance between any transmitter and receiver, the smaller the signal. Signal strength varies inversely by the square of the distance between transmitter and receiver. Range is also affected by the frequency of operation. The higher the frequency, the shorter the range for a given transmitter power output.

Power—The higher the power, the greater the transmission range. More power translates into increased communications distance up to a point. For portable units, higher power means shorter battery life or faster discharge.

Antenna gain—Some antennas focus the signal in a specific direction. Doing so gives the antenna *gain*, meaning it multiplies the power of the transmitter and the signal strength at the receiver.

Environment—Cell phones and any other microwave wireless device always transmit farther in clear open space. The ideal is direct line of sight (LOS), meaning that the two antennas can "see" one another. While cell phones don't have to have such a clear path to work, they always work better if they do. Environment also means transmitting from inside a building. Yes, radio waves do pass through walls and other obstructions but as they do they lose considerable strength as they encounter obstacles. Walls, ceilings, floors, and any other obstructions greatly attenuate (make it smaller) the radio signal. So if you are inside a car, shopping mall, office, or airplane, your signal loses over half its strength and that severely restricts your range.

Height—Getting your cell phone to the highest possible point will greatly increase transmission distance. This helps the LOS effect so important to reliable transmission. Getting higher typically is not practical, but almost nothing helps more than height, especially outside.

Receiver sensitivity—This means how much gain the receiver has. High sensitivity translates into greater range.

Multipath—Whenever you are transmitting in an environment with lots of obstructions, your signal will bounce off many objects and be reflected. Some reflected signals will get lost and never get to the receiver. Others will bounce off objects that will ultimately direct them to their intended destination. These reflected

Factors Affecting Range and Reliability to Radio Transmission—cont'd

signals will be delayed in time. Depending on factors such as operating frequency and distance traveled, these signals could arrive in phase and actually boost reception level. Or they could arrive out of phase and literally cancel the more direct signal that arrived earlier.

Noise—Do not forget that noise also affects communications distance and reliability. See discussion in Chapter 7.

THE CELLULAR CONCEPT

The original designers of the cell phone created a system that helps overcome the range and power problem described in the sidebar. If distances are kept short, then other limitations in power and environment are offset. The working word here is "cell." A cell or cell site is one of many transmit/receive stations set up to communicate with individual cell phones. Also known as base stations, these facilities are easily recognized by their tall antenna towers. Modern fourth-generation (4G) cell sites are referred to as eNodeB. The small building at the base of the tower houses racks of transceivers that share the big antennas at the top of the tower. Long coax cables carry the signals to and from the antenna. They actually look like pipes going up the side of the tower.

Cell phone systems have dozens to hundreds of cell sites. The overall network is called the radio access network (RAN). An ideal design is shown in Fig. 8.1A. Each cell represents an area covered by the base station antennas. Cell range and overall coverage are deliberately restricted by antenna height and radiation pattern as well as transmitting power. The hexagon-shaped cells are only theoretical. In reality, the shape of the cell is more circular or rather an irregular circular shape because of antenna characteristics and environmental characteristics that affect the cell shape (nearby trees, buildings, etc.) (see Fig. 8.1B).

While equal-size cells are desirable and operation is more predictable, in the real world, the coverage of each cell depends a great deal on the number of cell phone subscribers as well as the terrain and environment. In large cities with lots of people and buildings, smaller cell sizes are used to increase subscriber capacity and provide the most reliable coverage possible in a given area. Many cities have what are called microcells that may only cover one block or picocells that cover one area of a building. On the other hand, in rural areas and along major highways, the cell sizes are larger and cover fewer users. The cell coverage may look more like that in Fig. 8.2.

A key feature of the cellular concept is that by keeping the cell sizes small, the frequency channels assigned to cellular service can be reused. One frequency may carry different calls if the cell sites are far enough apart and do not interfere with one another. This frequency reuse concept multiplies the overall number of channels available to handle calls.

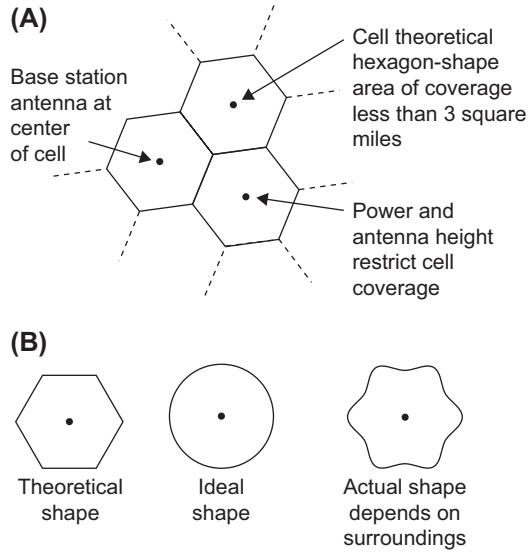

(A)
Base station antenna at center of cell
Cell theoretical hexagon-shape area of coverage less than 3 square miles
Power and antenna height restrict cell coverage
(B)
Theoretical shape
Ideal shape
Actual shape depends on surroundings

FIGURE 8.1 (A) Cell coverage of a given area. (B) Cell area covered depends on antenna pattern and environment.

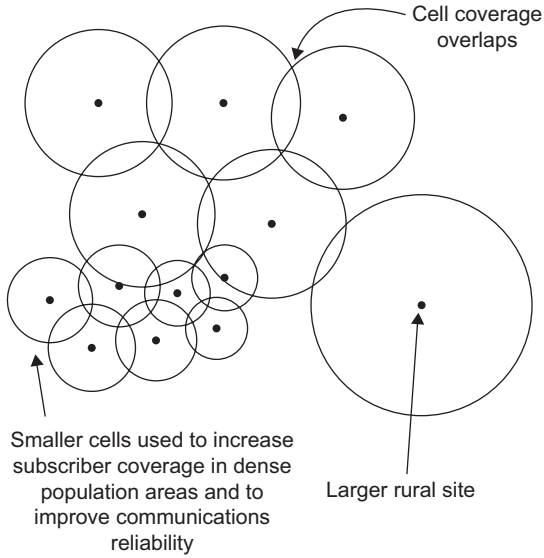

Cell coverage overlaps
Smaller cells used to increase subscriber coverage in dense population areas and to improve communications reliability
Larger rural site

FIGURE 8.2 How small and large cells cover an area.

One other factor to keep in mind is that in most cities, there are two or more cellular companies vying for your business. Each company has its own cellular system with base stations with coverage that overlays the cell coverage

of other companies. The competing systems do not interfere with one another because they usually operate on different frequencies with and sometimes different radio technology, and the cell phones they support know which base stations to talk to.

One other thing: when you are talking on your cell phone, you are talking to only one base station—typically the one closest to you since both the power and range of your handset and that of the base station are limited. If you are moving (such as in a car), you will eventually leave the coverage area of one cell and enter the coverage area of an adjacent cell. You never really know when this happens, but it is a pretty neat technical trick to make this happen. The process of having your call transferred from one cell site to another automatically is called the *handoff*.

All of the base stations are tied to a central office known as the *mobile telephone switching office* (MTSO) or *mobile switching center* (MSC). Many companies simply refer to it as the *switch*, as its main job is switching between base stations as well as linking to the main telephone system. The connection between the base stations and the switching station can be by copper cable or fiber optic cable or in many cases by a separate microwave wireless link. This is known as *backhaul*. If a cell site tower has one or more small "dish" antennas on it, you can bet that your signal eventually is communicated back to the switch via another wireless link.

The big job of the MSC is to control and keep track of everything. It validates you as a subscriber when you turn on your phone and make a call. It keeps track of how many minutes of time you use. And it will get messages from remote switches when you are in the roam mode outside of your usual home subscriber area. The cell phone companies have the ability to use other systems in most major cities and in many foreign countries, so you can use the phone virtually anywhere. Fig. 8.3 shows just what goes on when you turn on your phone and make or receive a call.

WHAT IS INSIDE A CELL PHONE?

A cell phone can legitimately be called the world's most complicated two-way radio. Sure, it is just a transceiver, but it uses practically every radio trick in the book to ensure that you can make your calls reliably anytime with minimal hassle. It is a two-way radio that is used just like any other phone you are familiar with. In other words, you do not have to say "over," "come back," or any other phrase when you are finished talking and want to listen, as with some two-way radios (citizens band, family radio, ham radio, aircraft, marine, etc.).

Simultaneous send and receive is referred to as *full duplex*. All telephones are full duplex. It is easy to do in the wired telephone system but complex and costly to do by radio. Yet, full duplex is what makes cell phones so comfortable to use. There is none of this "roger and over" stuff. What this means is that your

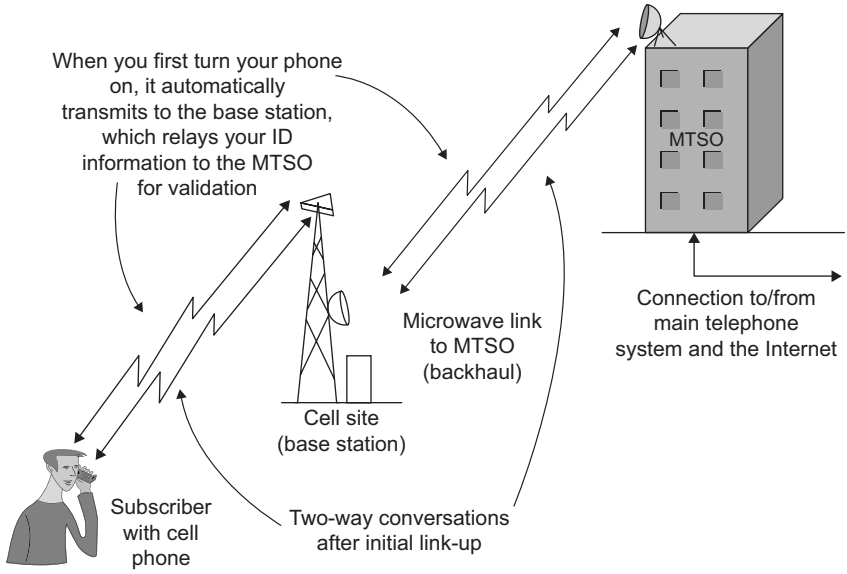

When you first turn your phone on, it automatically transmits to the base station, which relays your ID information to the MTSO for validation
MTSO
Connection to/from main telephone system and the Internet
Microwave link to MTSO (backhaul)
Cell site (base station)
Subscriber with cell phone
Two-way conversations after initial link-up

FIGURE 8.3 Cell phone basic operations.

transmitter and receiver are working at the same time. There is more about how duplexing works later.

Fig. 8.4 shows a very simplified general block diagram of what is in a cell phone. The receiver and transmitter making up the transceiver are obvious, and they share the single antenna. The transceiver is usually a single chip. What is not so obvious is what we call the baseband part of the cell phone. Baseband refers to the voice and data to be transmitted or received. In most modern digital cell phones, this is a very complex integrated circuit that handles the translation of voice between analog and digital, modulation and demodulation, and voice compression. All these functions are done digitally by a digital signal processor (DSP) or special DSP circuits in combination with a powerful embedded processor. This processor or a separate processor handles all the transparent housekeeping jobs of managing the touch keyboard and the LCD screen as well as the basic control features of the cell system, which also include automatic operating frequency selection and automatic power control under the direction of the cell site. The DSP also implements the messaging functions.

What Type of Cell Phone Technology Do You Have?

The cell phone radio and networking technologies have changed over the years. Each technology is known by its generation. We are currently in the fourth generation, and most new phones use a 4G technology known as Long-Term Evolution (LTE). But some older generation are still around.

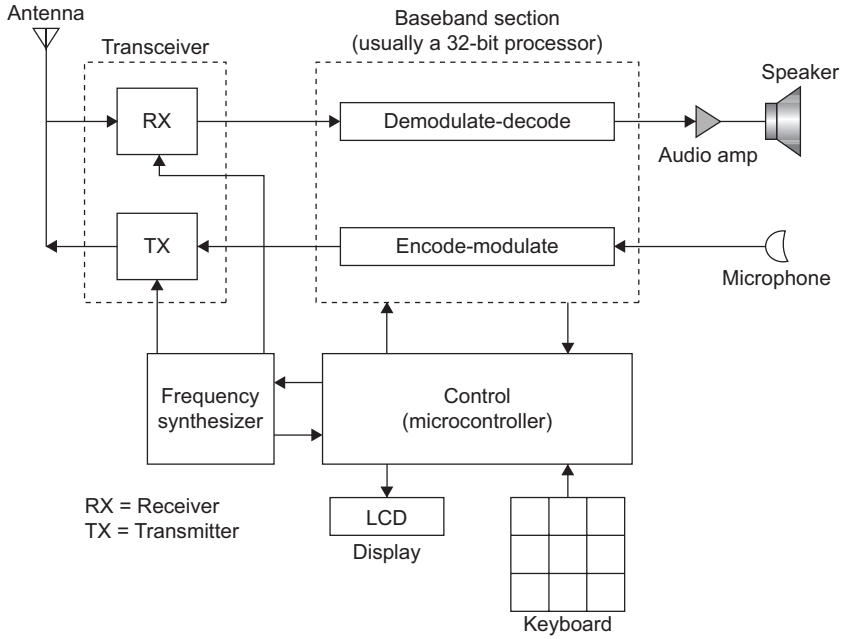


FIGURE 8.4 Block diagram of basic cell phone.

The first characteristic of a cell phone is the frequencies it uses. Most cell phones operate in the 800- to 900-MHz band where there are hundreds of channels for cell phone calls. Some 700-MHz spectrum is also now in use. Another range of frequencies is the so-called personal communications system (PCS) band from 1850 to 1990 MHz (1.85–1.99 GHz), which has hundreds of more channels. Some of the newer phones use the advanced wireless services (AWS), 1700- and 2100-MHz spectrum assignments. Some cellular companies also use spectrum in the 2300–2500 MHz range. Because of the higher frequency, PCS and AWS systems have a shorter range, and thus use smaller area cells, which means many more cell sites to cover a given area. Most cell phones actually operate on two or more bands that are assigned to your carrier.

Next, a cell phone is known by the technology and access methods it uses. The early original analog phones used first-generation (1G) technology, or FM, but have now been phased out. Most second-generation (2G) digital phones have also been phased out although there probably are some still in use in third world countries. Some third-generation (3G) cell phones are still with us to some degree; however, most phones today are of the 4G variety and fifth-generation (5G) is almost with us. A summary of these technologies follows.

GSM—The Global System for Mobile Communications (originally called Groupe Spécial Mobile) is the 2G digital system developed in Europe. It uses time division multiple access (TDMA), a digital system using digital

modulation and a method of multiplying the number of channels in a given amount of frequency spectrum. Your voice is converted to binary 1's and 0's before being transmitted. This allows the carrier to put eight subscribers in one 200-kHz-wide frequency channel, thereby greatly multiplying their subscriber capacity and income. GSM uses a form of FSK called Gaussian minimum shift keying (GMSK). GSM uses several enhancements that facilitate high-speed data transmissions such as the General Packet Radio System (GPRS) and Enhanced Data Rate for GSM Evolution (EDGE). These are no longer widely used.

CDMA—Code division multiple access is another 2G digital cell phone technology developed by San Diego–based Qualcomm Inc. The basic technology is known as *spread spectrum* where many signals are transmitted simultaneously over a very wide 1.25-MHz frequency band without interfering with one another. The original standard is called IS-95, and CDMA signals coexist in the same spectrum with TDMA systems in many areas.

cdma2000—This is the 2.5G/3G version of CDMA. It adds high-speed packet data transmission called 1xRTT with a data rate up to 144 kbps. A more recent upgrade called 1xRTT EV-DO has even higher data rates up to 2 Mbps, making Internet access a cinch. Many cdma2000 systems are still in operation around the United States and other countries.

WCDMA—This is wideband CDMA, which is a 3G technology. The access technology is CDMA, but it uses wider 5-MHz bands to provide greater user capacity and very high potential data rates from 384 kbps to 2 Mbps. WCDMA offers greater data speeds and services with higher subscriber capacity.

HSDPA/HSUPA—High-speed downlink packet access (HSDPA) and high-speed uplink packet access (HSUPA) are upgrades from the WCDMA system. Both use QAM to boost data speeds in the same 5-MHz channels. Data rates as high as 14 Mbps downlink and 5 Mbps uplink are possible. Most cellular companies have now implemented this technology. More advanced versions called HSPA or HSPA+ can give even higher data rates. Such systems are no longer widely used as it has been replaced by 4G technology.

cdma2000 Rev A and **Rev B**—These are more advanced CDMA versions that are used to boost data speeds in cdma2000 handsets. Rev A boosts download data rates to 3.1 Mbps using QPSK and 16-QAM in the standard 1.25-MHz channel. Rev B is not widely implemented, but can use three 1.25-MHz channels and boost download speeds to 14.7 Mbps and higher. Like the HPSA 3G technology these systems have been mostly replaced by 4G systems.

Long-Term Evolution—LTE is the current 4G cell phone technology. It uses an entirely different radio technology called orthogonal frequency division multiplexing (OFDM) to give even higher data rates. More on that later.

Today most phones are 4G LTE and will fall back to 3G if no LTE service is available. As this is written the 5G standards are still being developed and finalized.

DIGITAL MODULATION AND WIRELESS TRANSMISSION METHODS

In Chapter 7, basic digital modulation methods ASK/OOK and FSK were covered. These are not used except for an advanced FSK as used in GSM. Instead, all cellular systems used advanced digital modulation methods. This section provides a look at these techniques.

Quadrature Amplitude Modulation

Quadrature amplitude modulation (QAM) is a technique that mixes both amplitude and phase variations in a carrier at the same time. What this technique does is to allow higher data rates within the same bandwidth. See the sidebar on spectral efficiency. The technique consists of transmitting multiple bits for each time interval of the carrier *symbol*. The term "symbol" means some unique combination of phase and amplitude. The term M as in M-QAM indicates how many bits are transmitted per time interval or symbol for each unique amplitude/phase combination.

The simplest form of QAM is 2-QAM, more commonly called QPSK or quadrature phase shift keying. It is produced by the circuit shown in Fig. 8.5. It takes the serial bitstream and passes it through a 2-bit shift register producing two parallel bitstreams at half the rate. One is called the in-phase (I) bitstream and the other the quadrature (Q) bitstream. The I and Q signals are each applied to a mixer along with a local oscillator (LO) signal. The mixer output becomes part of the RF carrier. Note that the LO signal is applied directly to one mixer, but is shifted by 90 degrees and applied to the other mixer. The term "quadrature" means shifted by 90 degrees. The two mixer outputs are AM signals but at different phases. But when they are added together, the QPSK signal is generated. With this arrangement, you can transmit data at twice the rate of BPSK in the same bandwidth.

Fig. 8.6 shows how we illustrate this with what we call the phasor and constellation diagrams. Fig. 8.6A shows the amplitude and phase of each possible

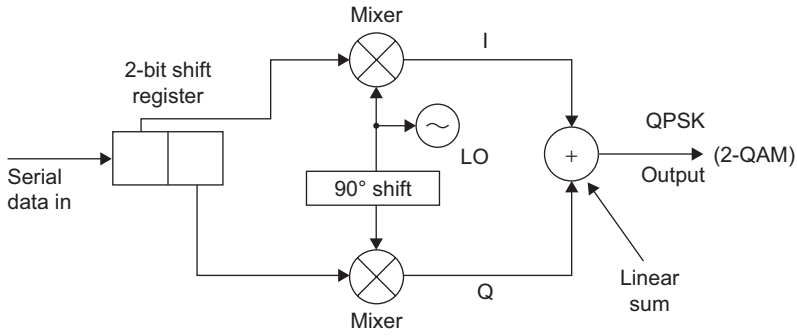


FIGURE 8.5 How QPSK is generated using mixers and a local oscillator shifted 90 degrees to produce in-phase (I) and quadrature (Q) signals that are summed.

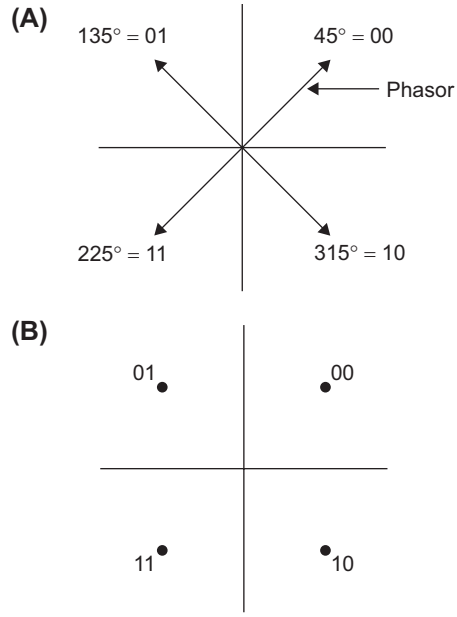


FIGURE 8.6 QPSK diagrams. (A) Phasor. (B) Constellation.

combination of 2 bits. The length of the arrow called a *phasor* is the amplitude, and its direction or angle is the phase. If the receiver gets a signal that is at a phase angle of 135 degrees, it means that the 2-bit combination 01 is being transmitted. The constellation diagram in Fig. 8.6B is usually shown without the arrows or phasors.

This technique can be modified to produce 16-QAM, which transmits 4 bits per time interval or symbol causing the data rate to quadruple in the same bandwidth. The circuit for producing 16-QAM is shown in Fig. 8.7. The 4-bit shift register produces two groups of I and Q bits. These are converted into four levels by a two- to four-level converter that works like a digital-to-analog converter (DAC). The resulting constellation diagram for 16-QAM is shown in Fig. 8.6 as well. Other common versions are 64-QAM and 256-QAM, which transmit 6 and 8 bits per symbol, respectively, in the same bandwidth. A 1024QAM is also an option in some systems.

QPSK and QAM modulation methods are common in cable TV for digital TV as well as high-speed Internet service. They are also used with satellites and any broadband wireless application. All modern cell phones and most other digital wireless schemes use this type of modulation because of its spectral efficiency.

Orthogonal Frequency Division Multiplexing

OFDM is a broadband modulation method like spread spectrum/CDMA. It takes a high-speed serial binary signal and spreads it over a wide bandwidth. The

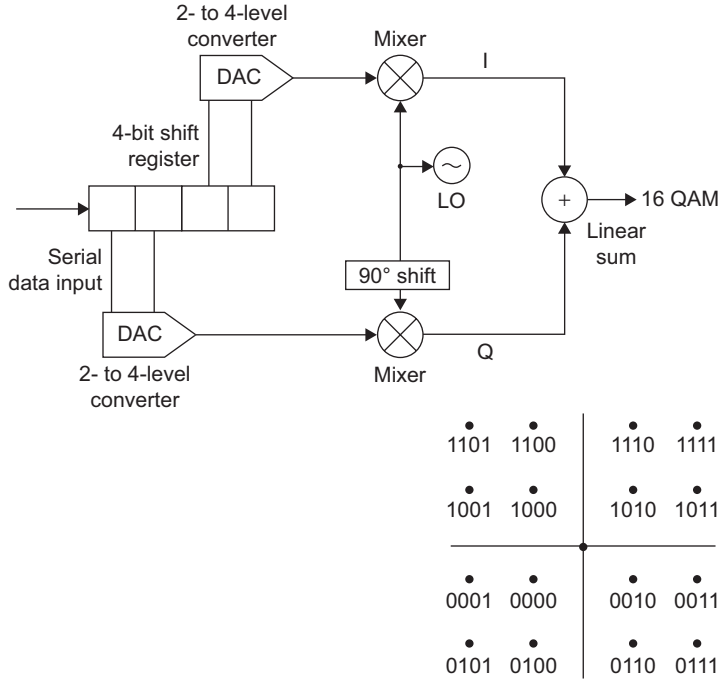


FIGURE 8.7 How 16-QAM is generated and resulting constellation diagram.

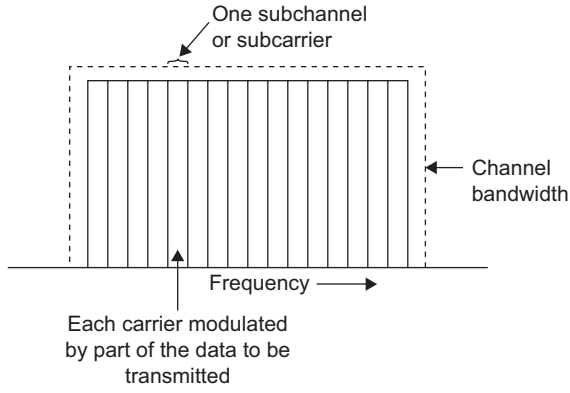

One subchannel or subcarrier
Channel bandwidth
Frequency
Each carrier modulated by part of the data to be transmitted

FIGURE 8.8 OFDM divides a channel into many subchannels or subcarriers, each of which is modulated by part of digital data to be transmitted.

serial data is passed through a circuit that maps out the constellation diagram for the modulation to be used. It then divides it into many slower-speed serial bitstreams. Each bitstream modulates a carrier on one of many adjacent carriers in the available bandwidth. This technique effectively divides a wide bandwidth into many narrower subchannels or subcarriers as shown in Fig. 8.8. Sometimes

dozens of channels are used, and in other cases hundreds or even thousands of carriers are used. The carrier frequencies are selected so they are orthogonal and as a result they will not interfere with one another even though they are directly adjacent. All the modulated channels are then added together and the combination transmitted in the available bandwidth. The type of modulation varies with the application but it is usually BPSK, QPSK, 16-QAM, 64-QAM, or 256-QAM.

The basic technique is shown in Fig. 8.9. The only practical way to create an OFDM signal is by using DSP. The DSP executes an algorithm called the inverse fast Fourier transform (IFFT) that creates the multiple adjacent modulated carriers. The DSP data is applied to DACs to create I and Q analog signals that are sent to mixers for creation of the final signal. That signal is then amplified by a broadband linear amplifier before being transmitted. At the receiver, the data is recovered by another DSP executing the FFT. The output is the original fast serial data.

OFDM seems impossibly complex while seemingly hogging spectrum space. Yet, it can transmit higher speeds in smaller bandwidths than most other types of digital modulation. It is very spectrally efficient. Furthermore, it is more resistant to multipath interference that can cause microwave links to lose data due to a reflected signal interfering with another or a direct signal causing cancellation and fading. Most of the new wireless technologies today use OFDM, including the LTE cellular systems. Some examples of other OFDM uses include wireless local area networks (WLANs) such as Wi-Fi, wireless digital subscriber line (DSL) Internet access, some (European) digital TV, and AC power line networking.

Multiple Input Multiple Output

Another technique for boosting speed within a given bandwidth is multiple input multiple output (MIMO). Also known as spatial multiplexing, it is the use of multiple transmitters transmitting to multiple receivers, each sending different bitstreams on the same channel. The high-speed serial data is

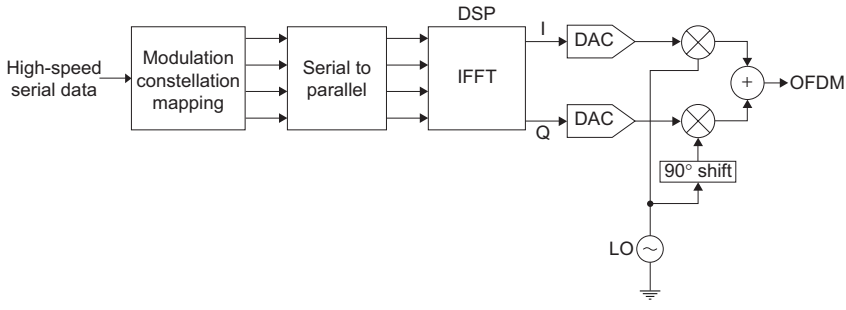


FIGURE 8.9 Generating OFDM is done by DSP and I/Q modulation.

divided into two, three, four, or even more bitstreams, and each is used to modulate a different transmitter but operating on the same frequency. The signals from each transmitter reach the antennas of each receiver along with any reflected signals. See Fig. 8.10, which shows four transmitters (Tx) and four receivers (Rx) or 4×4 MIMO. What allows the receivers to sort out each bitstream is the fact that each signal travels a different path and will have different characteristics or spatial signature that can be sorted out by DSP in the receiver.

There are several things that make MIMO practical. First, MIMO is used at very high frequencies, especially microwave (0.1 GHz). This means that antennas are short, and interantenna space may be one wavelength or more, which is required for MIMO to work. The distance between the antennas ensures different spatial paths with different characteristics that let the receivers recover each bitstream. Second, thanks to semiconductor technology, it is possible to make the multiple transmitters and receivers very inexpensively, typically all on a single silicon chip.

MIMO has several benefits. First, it allows a higher data rate in the same channel bandwidth. Using a 4×4 MIMO, for example, would boost speed by a factor of 4. Configurations of MIMO can be any combination of transmitters and receivers. The 2×2 mode is popular but 4×4 is also used. Second, MIMO provides a more reliable link. It actually takes advantage of the multipath problems that usually plague microwave wireless and makes it better. Finally, MIMO is usually combined with OFDM, which provides the ultimate data rate boost, reliability, and spatial efficiency. MIMO is already used in WLANs such as Wi-Fi. MIMO is also used with LTE Handsets typically have only two antennas, but the base stations have four or more.

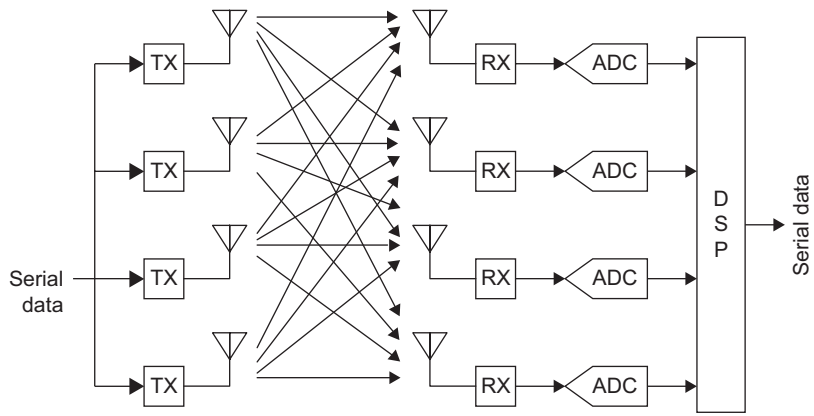


FIGURE 8.10 MIMO in a 4×4 configuration quadruples the data rate in an existing channel, while reducing the ill effects of multipath fading.

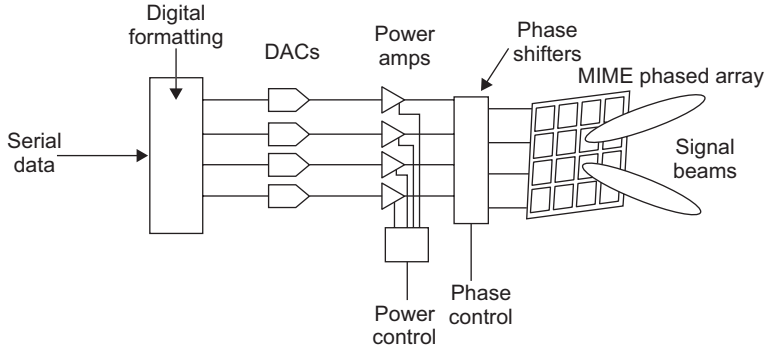


FIGURE 8.11 The concept of MU-MIMO using beamsteering with a patch-type phased array antenna.

An advanced version of MIMO called multiuser or MU-MIMO is also being widely adopted. Also called massive MIMO because it uses a large (64–1024) number of antennas combined to form what is called a phased array. Each antenna has a transmitter and receiver associated with it. By controlling the phase and amplitude of the signals sent to the antennas, the signal can be focused into a narrow beam creating gain in the antenna. Fig. 8.11 shows the concept with a 16-patch antenna array. In addition to beam forming, the signal beam can also be steered in different directions horizontally or vertically. Another feature is that separate multiple beams can be formed so that several different independent signals can be sent or received at the same time. By using massive MIMO, multiple users may be served by a single base station and higher data rates can be achieved.

Spectral Efficiency

Spectral efficiency refers to how much data you can transmit in a given bandwidth. It is usually measured in bits per second per hertz (bps/Hz). ASK/OOK and FSK have efficiencies of <1. Special forms of FSK, such as GMSK used with older GSM cell phones, are a bit better. BPSK has a spectral efficiency of 1. Table 8.1 gives the efficiencies of most of the popular digital wireless modulation schemes.

One last thing: the type of modulation is not the only thing that affects spectral efficiency. The level of noise in a channel also determines the number of bit errors that occur in transmission. The higher levels of QAM have more errors, so this limits their efficiency to some extent. Plain FSK, BPSK, and QPSK are very resistant to noise, so are more suitable in applications where noise is a problem. Noise and bit rates have to be traded off for good reliable transmission. And by the way, the spectral efficiency issue applies to wired as well as wireless communications channels.

TABLE 8.1 Spectral Efficiency of Selected Digital Wireless Modulation Schemes

Modulation Method	Spectral Efficiency (bps/Hz)
FSK	1
GMSK	1.35
BPSK	1
QPSK	2
16-QAM	4
64-QAM	6
256-QAM	8
OFDM	Depends on modulation of subcarrier and number of subcarriers
MIMO	Depends on configuration

ACCESS METHODS AND DUPLEXING

Access methods are wireless techniques that allow multiple users to share a given part of the frequency spectrum. Access methods are also called *multiplexing*. Multiplexing means allowing two or more signals to be transmitted *concurrently* over the same communications medium such as a cable or within a given frequency band. Access methods allow many subscribers to share precious spectrum space. And they provide the means to implement full-duplex simultaneous transmit/receive that most phone users expect. There are four types: frequency division multiple access (FDMA), TDMA, CDMA, and orthogonal frequency division multiplex access (OFDMA). For full-duplex operation, there are two methods—frequency division duplexing (FDD) and time division duplexing (TDD).

FDMA—A given bandwidth is divided into many narrower channels as shown in Fig. 8.12. A given radio will cover all of the bands but has the ability to select a specific operating frequency. GSM divides the band into 200-kHz channels. cdma2000 uses 1.25-MHz channels and WCDMA uses 5-MHz channels. The newer OFDM uses 5-, 10-, 15-, or 20-MHz channels.

FDD—Simultaneous transmit and receive is accomplished by using two different bands where half are used for transmit and the other half for receive. The transmitter and receiver operate at the same time but on different frequencies so they do not interfere with one another (see Fig. 8.12).

TDMA—With this method, a single-frequency channel is used, but the signal is divided into fixed-duration time slots into which digitized segments

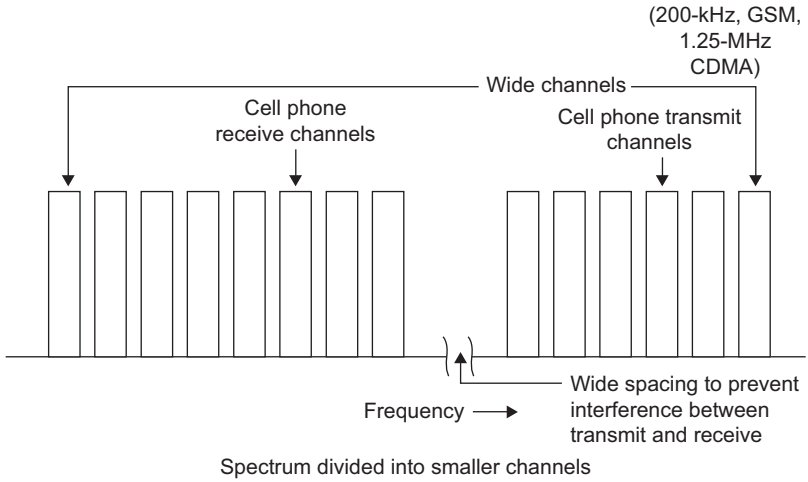


FIGURE 8.12 Frequency division multiple access and frequency duplexing use two separate bands of frequencies divided into individual channels.

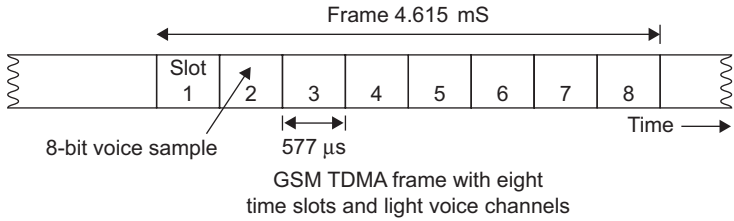


FIGURE 8.13 TDMA multiplexing divides a channel into sequential time slots for the digital data.

of voice or data are transmitted. In digital voice transmission, the analog voice signal is periodically sampled and digitized into a stream of binary numbers. These binary values are then compressed into a smaller number of bits by a vocoder circuit. The resulting bits are then transmitted to the receiver. With TDMA, binary values from two or more voice sources can be interleaved and sequenced, and then sent over the single channel. For example, in GSM systems, there are eight time slots, as shown in Fig. 8.13. The data is transmitted at a 270-kbps rate in a 200-kHz-wide channel. Each time slot contains 1 byte of the voice data for one phone call. The frame of eight signals is then repeated.

TDD—TDD facilitates concurrent send and receive by assigning transmitted signals in one time slot and received signals in another time slot. They share the same frequency channel. Because all this is happening at a high rate of speed, you cannot determine that transmit and receive are not simultaneous, although in reality they are not.

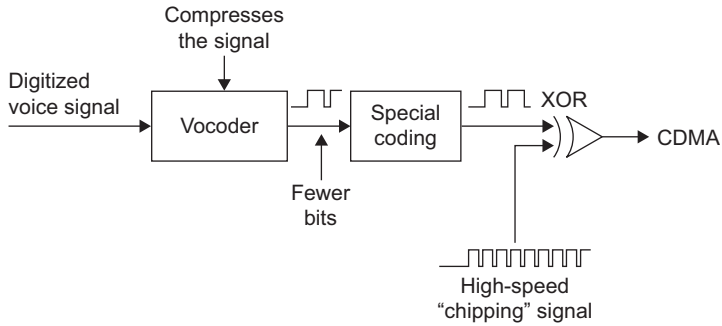


FIGURE 8.14 How CDMA is generated.

CDMA—This method uses spread spectrum technology. It takes the digitized voice and further processes it to give it special coding, and then spreads it over a wide bandwidth. In cdma2000 phones, the channel bandwidth is 1.25 MHz wide, and all cell phone signals are coded and spread over this bandwidth. The process goes like this: the analog voice signal produced by the microphone is digitized in an ADC, and then compressed by a special digital circuit called a *vocoder* or *voice coder*. This reduces the total number of bits and the speed of the digital signal. This vocoded signal is then mixed with a high-speed serial code signal, making it unique so that the receiver will recognize it. This is done with an XOR gate as shown in Fig. 8.14. The higher-frequency signal, at 1.23 Mbps, is called the *chipping data*. The resulting signal fills the 1.25-MHz channel. In WCDMA systems, the process is the same, but the chipping signal is 3.84 Mbps and the channel width is 5 MHz.

Using CDMA many cell phone calls can be transmitted on the same channel. They actually all mix together, but because they occur randomly with one another, they do not interfere with one another. Typically, up to about 64 users can share the same bandwidth. One signal simply appears as a low-level noise to another. The desired signal is picked up at the receiver by recognizing the unique code given to the transmitted signal. The two most common types of spread spectrum are direct sequence and frequency hopping. Direct-sequence spread spectrum is used in cell phones as illustrated in Fig. 8.14. Frequency hopping is used in Bluetooth wireless systems (see Chapter 9). Most duplexing is by FDD, but some of the newer versions of LTE also use TDD.

OFDMA—Access with OFDM is done by just assigning one or more of the subchannels to each transaction. With each subchannel 15 kHz wide, each is capable of carrying a compressed (vocoded) voice signal so that many calls or data transactions can be handled. In practice, more than one channel may be used, depending on the specific frequency assignments, bandwidths, and other features of the LTE system being used.

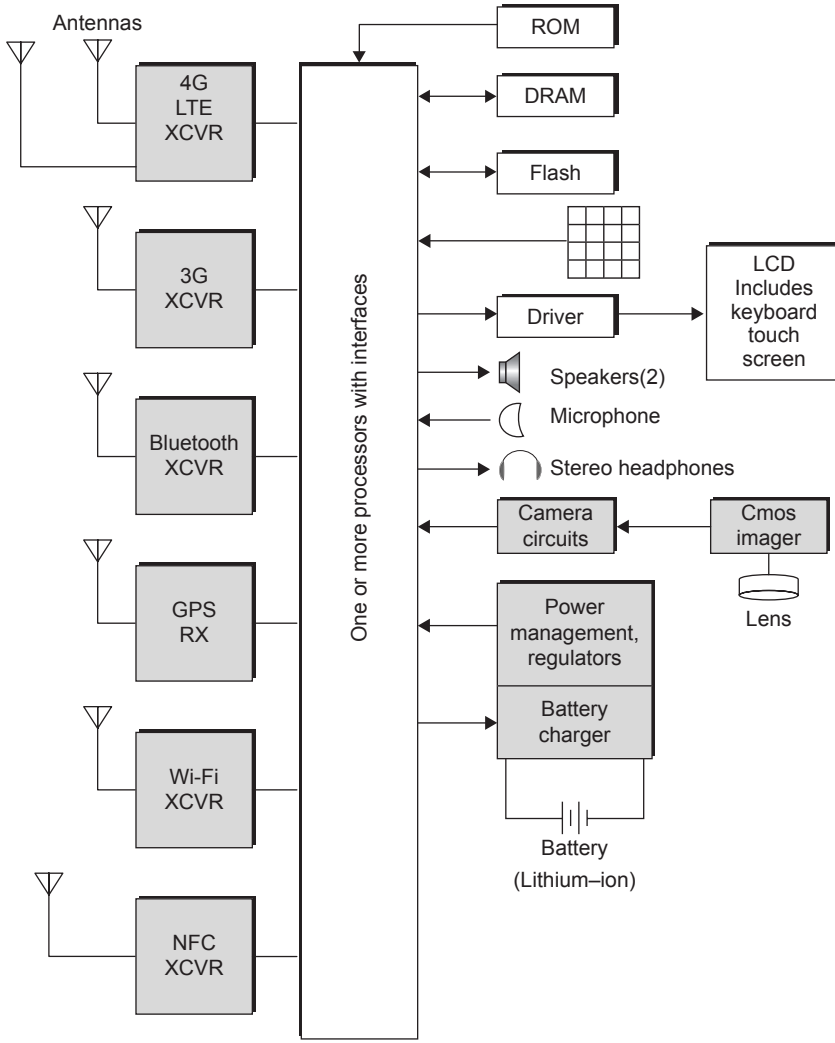


FIGURE 8.15 A block diagram of 4G cell phone with multiple radios and functions.

A LOOK INSIDE A 4G CELL PHONE

Fig. 8.15 shows the insides of a modern 4G smartphone. This one uses the LTE 4G technology, but is also backward compatible with 3G. There are separate radio transceivers (XCVR) for each. All of the baseband functions such as modulation and demodulation and handset management are handled by one or more processors. Dual core or quad core processors are used. One processor implements DSP. This handset also has a Bluetooth radio for the headset (not shown) and a Wi-Fi transceiver for Internet access via a WLAN access point or hot spot.

Most of the newer smartphones also contain a near-field communications transceiver for payment and access applications. These technologies will be covered in the next chapter. A global positioning system (GPS) radio provides navigation as well as fulfills the E911 location requirement. Note that most radios have separate antennas. In some cases if the frequency range is the same, an antenna can be shared. A camera for digital stills and video is included. The CMOS imager is the device that converts the light and color variations in the scene into electrical signals. Other light sensor types are used. The stereo headphones are for the music player. A recent addition to many smartphones is wireless charging using inductive coils. Finally, all smartphones have a massive amount of memory, both DRAM and flash. The power supply is a lithium-ion battery along with the charging circuits, regulators, and power management circuits.

THE LATEST CELL PHONE TECHNOLOGY

The cell phone industry is one of the fastest changing in electronics. New products come out almost daily. And new features and capabilities are invented regularly to keep the technology fresh and the sales continuous. Here is a snapshot in time of the latest cell phone developments.

Long-Term Evolution

LTE is the current 4G cell phone technology. Most modern smartphones use LTE with a fallback to 3G systems where LTE is not available. LTE uses OFDM with QAM modulation in 10 or 20 MHz channels along with MIMO to provide downlink data rates of up to 150 Mb/s. More recent versions such as LTE-Advanced and LTE-Advanced Pro use carrier aggregation (CA) to widen the bandwidth by combining up to 32 channels to achieve 100 MHz or more of bandwidth to get even higher speeds. With the right combination of CA, 256-QAM and 4×4 MIMO, LTE can achieve data rates up to 1 Gb/s.

The advanced versions of LTE-A also use unlicensed spectrum to further increase bandwidth. Features such as Licensed Assisted Access (LAA), LTE-WLAN (LWA), and LTE-U for unlicensed combine LTE spectrum and the unlicensed 5 GHz spectrum used by Wi-Fi 802.11ac/ax to boost downlink speed.

LTE-A Pro adds IoT/M2M connectivity (see Chapter 9). LTE-M uses only 1.4 MHz of bandwidth to achieve speeds up to 1 Mb/s. An ever more frugal version called NB-IoT uses 180 kHz to achieve a data rate to 250 kb/s. These new versions use less power and will find applications in IoT and in vehicle-to-everything (V2X) applications such as the advanced driver assistance systems (ADAS) and self-driving cars.

LTE Advanced also provides for a feature called device-to-device (D2D) communications. It lets LTE handset users talk directly to one another rather than through a cell site. Public safety officials are expected to adopt this version of LTE in lieu of more traditional two-way radio technologies.

LTE is the dominant worldwide cell phone technology. Many cellular operators are still up grading to the advanced versions. LTE works well and satisfies most of the demands of subscribers. However, the future is expected to require even faster networks. For that reason, the 5G technology is under development.

Fifth-Generation Wireless Overview

Several key trends are driving the development of a newer and better cellular system. One trend is the increased use of mobile video and the need to be able to handle 4K resolution video and virtual reality. Higher data rates (>1 Gb/s) are needed for some applications.

Another trend is the increase in connected devices using IoT or M2M technologies. Billions of devices may be connected, and many will use the cellular system that must be able to handle the increased number of subscribers.

In addition to a higher data rate, another major need is lower latency as it is critical to driving safety as well as many IoT/M2M uses in factory automation. Latency is the delay time between the initial triggering of some action and the instant the action occurs. Many robotic and other machine operations demand millisecond (ms) range latency. 4G radios can usually have a latency of 25 ms or more. 5G is expected to provide for a latency of 5 ms or less.

The 5G standards are being developed by the Third Generation Partnership Project (3GPP). The new standard is called New Radio (NR). Here is a summary of 5G NR features.

- Maximum data rates should be in the 1 to 10 Gb/s range depending on the bandwidth allotted and signal path environment. Typical mobile data rates should be hundreds of megabits per second.
- To achieve these data rates, more bandwidth is needed and in many instances new spectrum will be needed. Some systems will use available spectrum below 6 GHz. However, most 5G systems will use the millimeter wave (mmwave) bands. In the United States the 27–28 and 37–40 GHz bands have been allocated to 5G with most operators are building systems in the 28 GHz band.
- CA (carrier aggregation) will be used to further increase bandwidth to support the desired higher data rate. Contiguous or noncontiguous bands as well as unlicensed spectrum can be aggregated to achieve the desired bandwidth.
- Modulation will be some variation of OFDM. Multiple schemes have been considered. The final standard has not been announced. QAM up to 256-QAM will be incorporated.
- TDD and traditional FDD will be used. By using TDD only half the spectrum is needed.
- The 5G network is expected to be made up of small cells instead of the larger macrocells common today. Small cells including their antennas, the size of a loaf of bread, can be attached to light poles and the sides of buildings rather than require separate towers. Indoor units will also be common. Multiple small cells are needed to cover a given area because of the short range of mmwave signals.

- Massive MIMO is key feature of 5G. Using more than 64 antenna systems, the new cell sites can handle higher data rates and multiple users can be accommodated with beamforming. Beamforming implements spatial multiplexing that enables frequency reuse. Beamforming also increases signal power and permits small cells to avoid interference and establish more reliable links.
- A key feature of the 5G network is the use of software-defined network (SDN) and network function virtualization (NFV) software. These software technologies will help the carriers to manage a large number of small cells as well as to rapidly reconfigure the network and provide faster easier addition of new cells or subscribers.

Some 5G pilot evaluation systems are being tested as this is written and some prestandard networks could be in limited use in 2018. Final standards are not expected until 2019. Full build-out may not occur until 2020.

Most cell phones today are smartphones with advanced features that expand its use. There are about a dozen smartphone manufacturers, but the market leaders are Apple's iPhone and Samsung's Galaxy series. Over a billion smartphones are sold annually. There are too numerous to mention here, and they go out of date monthly or yearly. Here is a general summary of their capability.

High-speed data capability. Most smartphones use 4G LTE technology, so they can deliver as fast a data rate as your home Internet connections, usually 10–20 Mbps or better on average. Peak rates are over 100 Mbps under some favorable conditions.

Internet access. A built-in browser lets you access the Internet. The main limitation is the small screen size, which prevents you from doing as much as you would like, but you can still do it.

Email. Email is one of the key features of a smartphone. It lets you stay in touch without a PC or laptop.

Messaging. It goes without saying that text messaging is a main data feature.

Digital camera. Most smartphones have an excellent high-resolution camera built in. The camera does have about 12 megapixels of resolution or more. All high-end smartphones contain both front and back cameras.

Camcorder. All of the digital cameras have video capability as well. The main limitation is the amount of memory available to store videos.

MP3/iPod. A music player is a standard feature of many smartphones. The key here is to have sufficient flash memory to store the songs you want.

WLAN access. You will learn more about this in the next chapter, but a smartphone has a built-in separate transceiver to connect to a Wi-Fi hot spot or other access point in airports, hotels, coffee shops, and other locations just like a laptop. You can access the Internet or email as an alternative to doing it through the cellular network.

Bluetooth. Bluetooth is another short-range wireless technology covered in Chapter 9. It is used in smartphones for wireless headsets. A headset contains a headphone and a microphone that fits in the ear. It talks to the cell phone wirelessly via a Bluetooth wireless link.

Near Field Communications. NFC is a short-range wireless technology used for automatic payment, transportation, or facility access.

GPS and maps. The GPS is the worldwide satellite navigation system. All phones have a built-in GPS receiver so that you can find your way. All phones include full navigation software, display, and maps such as those in personal navigation devices (PNDs) like those from Garmin and Tom Tom.

Apps. Apps or applications are software programs that implement special functions or services. Games are a popular type but others include banking, investment, special calculators, and social media such as Facebook, Twitter, LinkedIn, Instagram, and others. Millions of apps are available and convert your smartphone into a useful computer.

Location Technology

Location technology refers to systems and circuits that are designed to pinpoint the location of a cell phone in use. This can be done now to a certain extent, as a carrier can always determine which cell site a phone is currently using. That only locates the phone within an area of a few miles. The Federal Communications Commission (FCC) has mandated that all cell phones can be located within 50–100 ft in case of an emergency. This is part of the E911 system for all cell phones. E911 means that your cell phone company has a system that will send your physical location to emergency services if you call 911 from your cell phone. Most systems use GPS, but others may have another type of location technology. The whole thing is transparent to a user, and most users actually do not know that their phone has this capability.

The location capability has many concerned for privacy reasons. But if you do not want to be located, turn off your phone. Otherwise, learn to live with it, as it may save your life 1 day. Location technology is also supposed to lead to services that are based on location, such as advertisements for restaurants and other businesses near you.

When GPS is used, the GPS receiver computes your coordinates from the satellite signals and sends them to the carrier for use if called for. Most systems can usually pinpoint you within 50 ft or so depending on terrain and environment.

Project 8.1

Examine a Base Station

Go look at a cell site. The wireless phone company will not let you inside, but you can drive close to many and examine what you can see. Especially note the antenna arrangement at the top of the tower. Most have a triangular arrangement of three antenna arrays that divide the coverage into three 120-degree wide areas. You will see multiple coax cables going up the tower to carry the received and transmitted signals. Check for one or more backhaul dish antennas that connect the site to the main cellular system.

Chapter 9

Networking: Wired and Wireless

All Devices Talking to One Another

In this Chapter:

- Types of networks defined: WAN, MAN, LAN, and PAN.
- Ethernet, Sonet, and other wired networking technologies.
- Internet transmission fundamentals.
- Wireless networking technologies, including Wi-Fi, Bluetooth, ZigBee, and others.
- Broadband technologies.
- Introduction to the Internet of Things.

INTRODUCTION

You already know from reading this book that virtually every electronic product has a digital computer built into it in the form of an embedded controller or microcomputer. But one other fact about electronic equipment that you may not know is that a large percentage of these devices are now being interconnected to one another to form networks. This is particularly true of computers. After all, what computer today is not connected to some form of network? And while we may be nearing the point where all computers are networked, the trend continues toward networking many other noncomputer devices. This chapter takes a look at networking concepts and the most popular forms of networks being used today, both wired and wireless.

IS EVERYTHING NETWORKED?

A network is just a system of people or things that are connected to one another. If someone was to ask you to give an example of a network, you probably would use the computer network definition. But there are all sorts of other networks in which we all participate in some form or another. One of the biggest networks is our interconnecting road system. Our highways and byways interconnect cities with one another and provide transportation routes for people and goods. The railroad is a massive network. You could also call the airline system a massive network of cities connected by airplane flights. Our whole electrical grid is a massive network.

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00009-6
Copyright © 2018 Elsevier Inc. All rights reserved.

And one of the largest networks in the world is the telephone system, both wired and wireless. And then again, let us not forget the Internet itself that connects us all to everything else. For our purposes here, our network definition is a system designed for communications via computers talking to one another or individuals talking to one another over cell phones. In all cases, a network is involved.

TYPES OF NETWORKS

There are lots of different ways to interconnect individual computers or other electronic products. You can do it by electrical cable or fiber optic cable, or you can do it in a wireless manner. In any case, each computer or user in the network is called a *node*. The goal of a network is to connect each node to all other nodes in some way so that they can communicate. Over the years, several different levels of networks have evolved.

Wide Area Networks

A wide area network (WAN) is the largest network of all, and we could consider the entire telephone network or the Internet as a large WAN. Sometimes WANs are smaller and may be localized to a country, a state, a city, or other large geographical area. The Internet is certainly a WAN. Most WANs are made up of fiber optic cable so that they can carry lots of data at very high speeds.

Metropolitan Area Networks

A metropolitan area network (MAN) is a network that covers a smaller geographical area such as a city or a large college campus system. Good examples of MANs are the local telephone company and your local cable TV company. MANs are also widely used in large companies and in governments to interconnect their computers. Most MANs are also implemented with fiber optic cable to maintain speed and data capacity.

Local Area Networks

A local area network (LAN) covers a small group of computers, typically a thousand computers or less. LANs are implemented in companies, small businesses, and even in homes. A LAN may only have a couple of users but could have several hundred, depending on the circumstances. Even two connected PCs at home comprise a LAN. In most cases, LANs are connected externally to a MAN or a WAN for external communications.

Personal Area Networks

Most personal area networks (PANs) are short-range wireless networks. A personal area network (PAN) is formed when two or more computers or cell phones

interconnect to one another wirelessly over a short range, typically less than about 30 feet. Most PANs are what we call ad hoc networks that are only set up temporarily for a specific purpose. The Bluetooth headset option on a cell phone is an example of a PAN.

Home Area Networks

A home area network (HAN) is a network inside the home used to provide monitoring and control over energy usage. It connects to the utility's electric meter and monitors energy usage so the home owner can see what energy is being used and where. It is also used to give the utility a way to control the heating and air conditioning to save energy. The HAN also provides a way to conveniently turn appliances off and on. The HAN may use wireless or communications over the AC power line. The HAN is the home portion of the national Smart Grid effort to conserve energy.

Storage Area Networks

A storage area network (SAN), as its name implies, is a network that interconnects large data storage devices to computers and to one another. Large arrays of hard disks are usually set up to store massive amounts of data needed by business, the government, and other organizations. The SAN provides a way to access all this information in a fast and easy way.

Network Relationships

As it turns out, the different types of networks are connected to one another, the result being one massive network. Fig. 9.1 is an example. For example, local LANs are connected to MANs, while the MANs themselves are connected to WANs, and so on. In this figure, the circles represent PCs while the squares represent network connecting points. These include servers, the computers that manage LANs and MANs; routers that determine connections in the network; and add/drop multiplexers that put data on the network and take it off. All the interconnecting links are fiber optic cable except for the copper cable in the LANs. This complex hierarchy essentially lets any computer talk to any other computer under the right conditions. The Internet implements such a hierarchy of networks.

NETWORK INTERCONNECTION METHODS

As you can imagine, there are lots of different ways to connect computers or other electronic devices to one another. For example, you could run a cable between each of the computers you want to interconnect. The result would be a large, complex, and very messy and expensive interconnection system. It is called a *mesh*. Except for a few computers, such systems are not used. Instead,

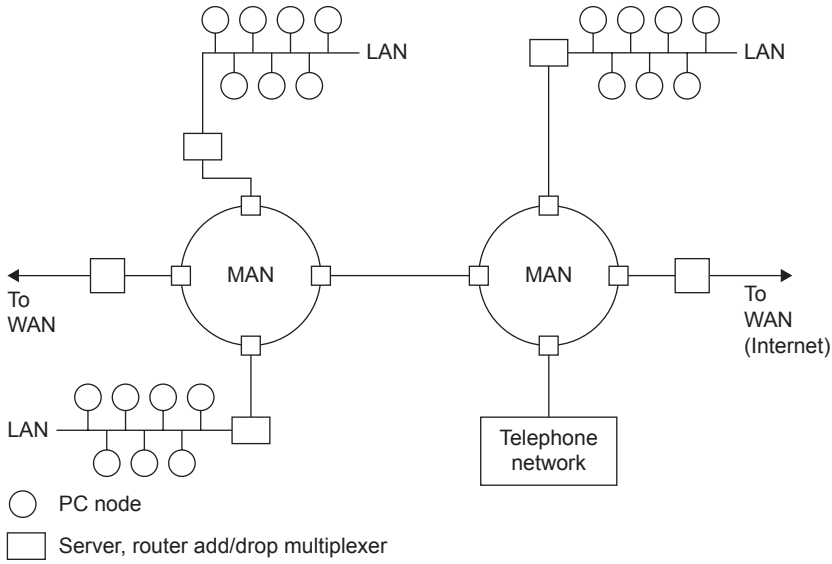


FIGURE 9.1 How LANs, MANs, and WANs connect to form a huge worldwide network of computers and other devices.

over the years, several different interconnection methods called network topologies have emerged. These are the star, the ring, and the bus, all simply illustrated in Fig. 9.2.

In the *star* method, each node is connected to a central control computer or server that manages the interconnections from any PC to any other. In the *ring* interconnection, the computers are simply connected into a single closed loop. Then data is transferred from one computer to the next by sending it around the ring. The computer destined for the information will recognize it and grab it off the ring as it comes by. The *bus* method of interconnection is one of the most popular, as it is simply a common cable or connecting point to which all computers are attached. The problem with the bus is that there can only be one sender or transmitting party of the information on the bus at a time. This requires some method of managing who transmits to whom and when. All nodes can receive.

The mesh network mentioned earlier is a messy thing to implement with cables. However, it can be implemented wirelessly. In a mesh, all nodes can talk to all other nodes within their range. This is advantageous in that there are multiple paths for data to take if one path should be blocked for some reason. More on that later.

WIRED NETWORKING TECHNOLOGIES

Wired networks use three types of cable: twisted pair, coax, or fiber optic. The telephone system has used twisted-pair cable from the very beginning, and it is

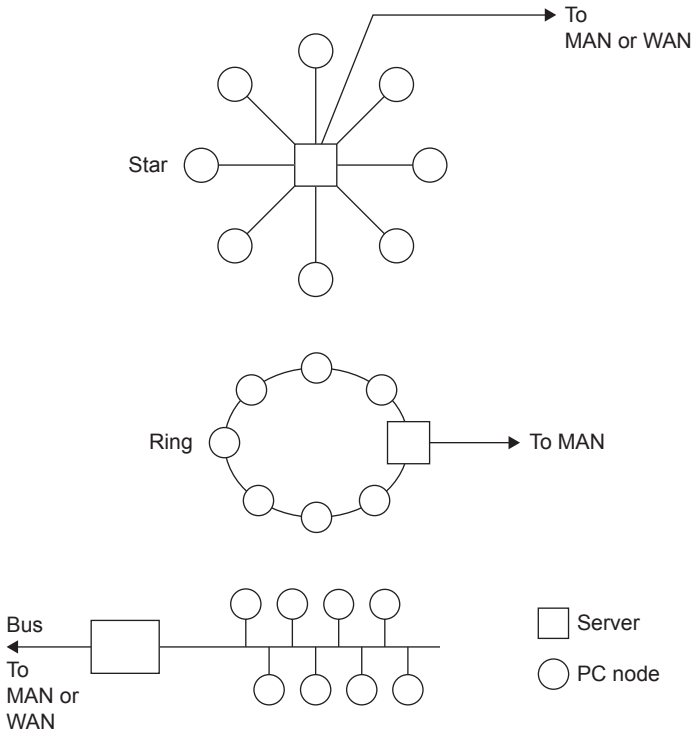


FIGURE 9.2 Three main networking topologies—star, ring, and bus. Bus is the most widely used.

still in use today. It is also the predominant way that LANs are interconnected. Coax cable was once popular but is not widely used today except in cable TV systems. Fiber optic cables were not practical until the 1970s, but since then have been developed into the best way to wire computer networks because of their high speed and low loss.

Types of Cables

Coax cable was the original networking medium (see Fig. 9.3). It has a copper wire center conductor surrounded by an insulator such as Teflon or another type of plastic that in turn is usually covered with a wire mesh braid. A plastic outer jacket covers the whole thing. The center wire and the mesh are the two connection points. Coax can handle frequencies up to many gigahertz. But it has high losses over long distances. Coax is mainly used in cable TV networks.

Twisted pair is the widely used cable for telephones and LANs. It consists of two solid insulated wires twisted together as shown in Fig. 9.4. Most telephone or LAN cables contain multiple pairs. Typical LAN cables have four pairs in a single cable. These cables are standardized and categorized as shown in

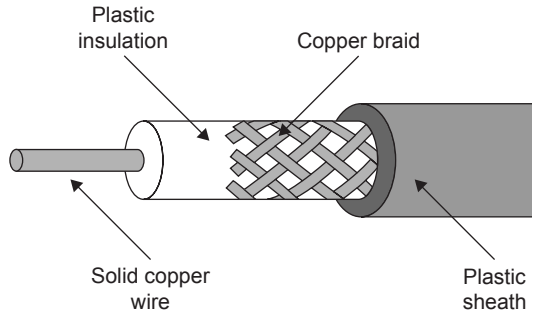


FIGURE 9.3 Coax cable. It is now mainly used in cable TV networks. The most common is RG-6/U and uses F-type or BNC connectors.

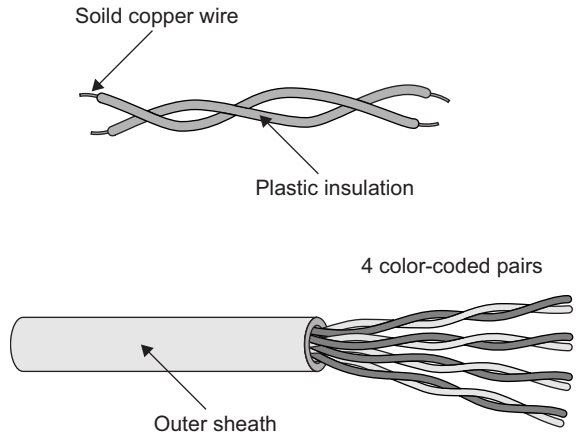


FIGURE 9.4 Twisted-pair cable. Initially used for telephones and is still used. Computer network cables use four twisted pairs. A shielded version is available where noise is a problem.

Table 9.1. CAT5 and CAT5e are the most common. The eight wires are usually terminated in a connector called an RJ-45.

Fiber optic cable consists of a thin glass or plastic center piece surrounded by a plastic outer cover. Then that is further wrapped by an outer plastic covering (see Fig. 9.5). Light waves are passed down the center glass or plastic cable. Most light comes from an infrared (IR) light laser. You cannot see IR but it is light nonetheless. IR light is what your TV remote control uses. The IR light is pulsed off and on to create binary signals. These are picked up at the receiving end by a light detector and converted back into binary 0 and 1 voltages (see Fig. 9.6).

Over the years, dozens of different wired networks have been developed. But in the past 2 decades, only two types of wired networks are dominant: Ethernet and synchronous optical network (Sonet).

TABLE 9.1 Types of Twisted-Pair Cable

Category	Maximum Data Rate	Application/Comment
CAT5	100 Mbps	Ethernet LAN, telephones
CAT5e	1 Gbps	Ethernet LAN
CAT6	10 Gbps	Ethernet LAN, video
CAT7	10 Gbps	LAN, point to point

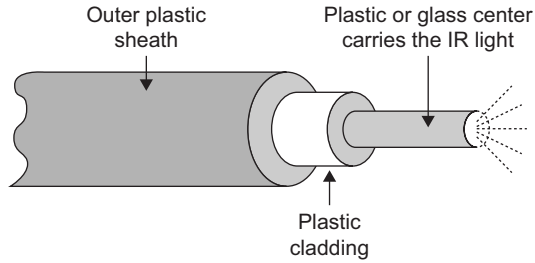


FIGURE 9.5 Fiber optic cable. It is nonconductive because it is made of plastic and glass, and is used to transmit data as infrared (IR) light pulses.

Ethernet

Ethernet was originally developed as a LAN in the 1970s. It used coax cable in a bus topology to interconnect multiple computers. Ethernet is also known by its Institute of Electrical and Electronic Engineers (IEEE) standard designation 802.3. Today, Ethernet is the dominant networking technology for LANs and is often used in MANs and WANs.

There are many variations of this technology, but the most common one uses unshielded twisted-pair cable. The bus topology is generally implemented inside a piece of equipment called a *hub* or *switch* (see Fig. 9.7). The cable from each computer or other device is connected to one of the jacks on the hub or switch. The hub or switch connects to a master computer called a *server* that manages the network. Generally speaking, connections to the hub or switch are limited in length to about 100 m or 300 feet.

The initial Ethernet LAN had a maximum data rate of 2.93 Mbps over coax. When Ethernet was standardized, the basic data rate was 10 Mbps. Over the years, Ethernet has been improved and developed to create versions with data speeds over twisted-pair cable of 10 Mbps, 100 Mbps, 1 Gbps, and 10 Gbps. Two new versions operate at 2 Mbps or 5 Mbps. While 10 Mbps can be implemented over a single twisted pair, to achieve speeds of 100 Mbps, 1 Gbps, and 10 Gbps, all four twisted pairs in the CAT5/6 cable are used. The data is divided between and transmitted in parallel at the same time using special multilevel encoding that permits such higher data rates to be achieved.

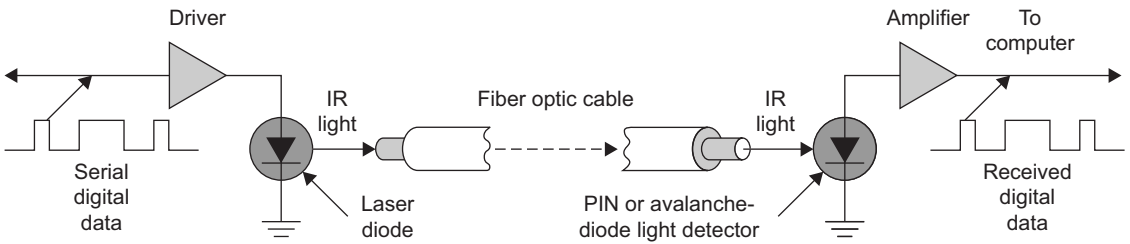


FIGURE 9.6 How binary data is transmitted over fiber optic cable.

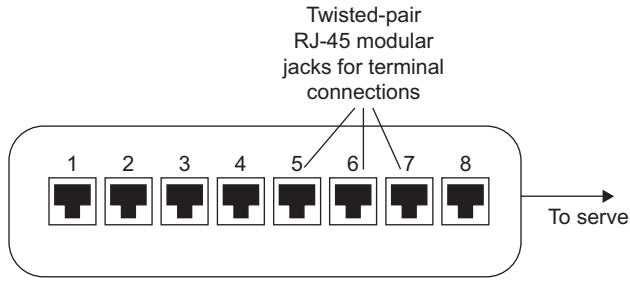


FIGURE 9.7 Ethernet hub or switch implements a bus that is accessed by RJ-45 connectors and twisted-pair cable.

Preamble	Start of frame delimiter	Destination address	Source address	Length	Data	Frame check sequence
7 bytes	1 byte	6 bytes	6 bytes	2 bytes	46–1500 bytes	4 bytes

FIGURE 9.8 Ethernet frame or packet.

There are also versions of Ethernet that use fiber optic cable. Fiber optic cable is normally used on the 1-Gbps and 10-Gbps versions. The latest versions of Ethernet provide 40-Gbps, 100-Gbps, and 400 Gbps data rates. A one terabit per second (1 Tbps) version is being developed.

How Is Ethernet Used?

Ethernet uses a bus topology connection where only one node can transmit at a time. This requires the use of an access method that permits the nodes on the bus to share it. Ethernet uses a technique known as *carrier sense multiple access with collision detection* (CSMA/CD). This is part of the IEEE 802.3 standard. Essentially what happens is that if a computer wants to transmit, it monitors the bus, and if no one is transmitting, it will begin transmitting its signal. If someone else tries to transmit at the same time, a collision occurs and both computers stop transmitting. Each will wait a random period of time and then try again. Whoever captures the bus first will be allowed to transmit. The data is transmitted over the bus, and any computer connected to it can receive it. However, typically the transmission is only intended for one other computer. To identify that computer, each is given an Ethernet address that is transmitted along with the data to be sent.

The data to be transmitted are packaged together in a group of bits called a packet. Fig. 9.8 shows what a typical Ethernet packet looks like. The preamble consists of 7 bytes of alternating 1's and 0's that help the receiving computer establish clock synchronization with the transmitting computer. The start frame delimiter presents a unique 1-byte code indicating that a frame of Ethernet data is to be transmitted. Next, a 6-byte destination address identifies the desired receiving node. The next 6 bytes identify the sending node. This is followed by

another 2 bytes of data that indicate how long the data message is. The block of data is then transmitted. It can be any length from about 46 to 1500 bytes. The packet ends with a frame check sequence that is essentially a unique code designed for error detection and correction. If bit errors occur during transmission, the receiving computer can perform specific logic functions that allow the error to be detected and then corrected.

While Ethernet started out as a LAN, it has morphed into other larger forms of networks. Because of its high-speed capability with fiber optic cable, it is also used to form MANs and even WANs. A special version for MANs and WANs is called *Carrier Ethernet*. There is also a version of Ethernet used in SANs, called *Internet Small Systems Computer Interface* or *iSCSI*.

More recently Ethernet is now the networking technology of choice in industry. Factories and plants now use Ethernet to connect computers, machine tools, robots, motor drives, and other manufacturing equipment. Ethernet is also being adopted for use in cars and trucks. It interconnects all of the many embedded controllers that operate the various subsystems such as emissions control, braking and stability, and safety. Another automotive use of Ethernet is in connecting infotainment equipment such as the radio, audio, video, and navigation.

Synchronous Optical Network

Sonet means *synchronous optical network*. Also known by its international standard name, *synchronous digital hierarchy*, this fiber optic network system was designed specifically for high-speed data transmission in telephone networks and computer systems. Basically, Sonet defines how data is transmitted over the fiber optic cables. This includes the data format as well as data speeds. Table 9.2 shows the various standardized transmission speeds from 51.84 to 39.812 Gbps. The bulk of Sonet installations, which are used primarily in the telephone networks and the Internet, use 2.488 Gbps (also generally called 2.5 Gbps) and 9.953 Gbps (generally referred to as 10-Gbps Sonet). More

TABLE 9.2 Sonet/SDH Designations and Data Rates

Sonet Level	Data Rate
OC-1	51.84 Mbps
OC-3	155.52 Mbps
OC-12	622.08 Mbps
OC-48	2.488 Gbps
OC-192	9.953 Gbps
OC-768	39.812 Gbps

recently, new 39.812 (40) Gbps networks are being built for the Internet. Data is transmitted in fixed-length frames made up of 810 bytes, most of which is data. The network topology is either point to point or in a ring.

Most big WANs and MANs use the Sonet system. However, Sonet is often used to transmit other data, including the telephone company T1 and T3 line data, asynchronous transfer mode (ATM), frame relay, and other telephone company formats. It is also widely used to carry Ethernet packets as well as the unique packets that are part of the Internet protocol. Today, Sonet equipment is gradually being phased out in favor of the optical transport network (OTN).

Telephone Data Systems

When the wired telephone system converted to digital many years ago, several key data transmission standards were developed. The most common are the T carrier systems, as well as frame relay and ATM. The most widely used digital telephone networking standard is the T-1 system. It was developed to transmit 24 digitized telephone lines over a single cable. The voice signals were digitized into 8-bit chunks and then transmitted sequentially over a T-1 line from one central office to another. The basic T-1 frame format is shown in Fig. 9.9. It consists of 192 data bits made up of 24 bytes representing individual chunks of telephone calls. An additional synchronizing bit is added. The result is a T-1 signal that transmits at a rate of 1.544 Mbps. And while T-1 is still widely used for digital telephone calls, it is also used for broadband computer data connections and cell phone backhaul.

There are other T carrier systems that are used to multiplex T-1 lines onto larger cables. The most common is the T-3, which allows dozens of T-1 lines to be multiplexed on a single cable at a 44.736-Mbps data rate.

Frame relay transmits data mostly in telephone systems. Both the T carrier and frame relay are synchronous systems, meaning that they are synchronized to a master clock signal.

Asynchronous transfer mode, as its name implies, is an asynchronous system that transmits data in packets. Each packet is made up of 53 bytes—5 bytes for a header that designates the destination and a 48-byte payload segment. Packets may be digital voice or computer data.

All these systems still exist to some degree but they are gradually being replaced by Ethernet and the OTN.

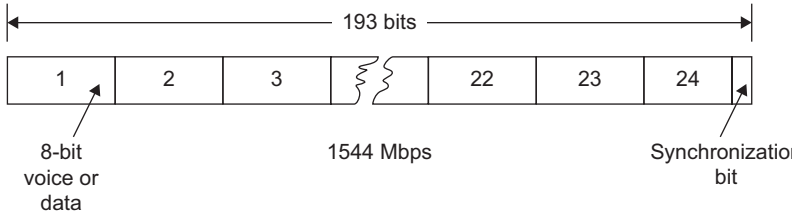


FIGURE 9.9 A T-1 data frame commonly used in digital telephone systems as well as data interconnections in networks.

Optical Transport Network

The OTN is a technology used to implement the Internet backbone network. This is the core long haul fiber optical network that connects the world together. OTN uses special polarization and modulation techniques to transmit data rates of 40, 100, and 400 Gbps.

HOW THE INTERNET WORKS

The Internet is an enormous WAN covering the entire world. It consists of many superfast, fiber optic cable links that are generally referred to as the backbone of the network. These high-speed links are owned by companies and governments and provide connection points for companies, governments, WANs, Internet service providers, and hosts for websites. These connection points are known as network access points (NAPs). See Fig. 9.10. There are dozens of NAPs in the United States, and they provide the link to the backbone connections. These backbone connections are worldwide. Because they are complex and interlinked, they are often referred to as the Internet cloud. Since data being transmitted from one point to the other can go by multiple paths in the backbone, there is no way to know the exact path, so the cloud designation is appropriate. You put the data transmission into one NAP entry point to the cloud, and it

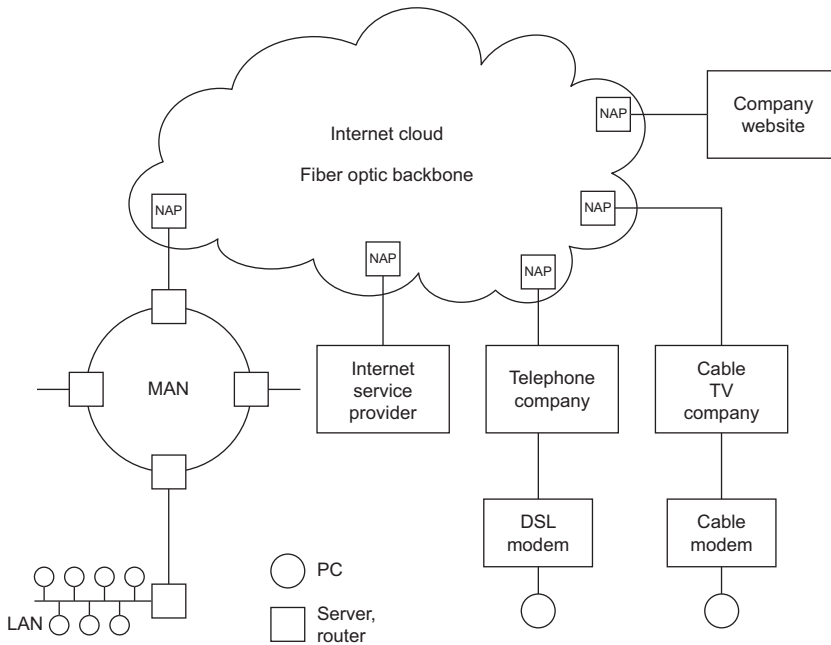


FIGURE 9.10 Internet illustrated as cloud of fiber backbone connections through network access points (NAPs) that attach to WANs, MANs, and LANs.

comes out in another. From there it goes to other MANs and LANs for connections to other networks and to individual users.

Data is transmitted over the Internet using a standardized method referred to as TCP/IP. This means transmission control protocol/Internet protocol. Both are protocols for building packets that are transmitted over the Internet.

Assume that a LAN and MAN using Ethernet want to transmit information over the Internet. The Ethernet packets are then sent to a NAP where they are assembled into the packets that actually get transmitted over the fiber optic cable. The TCP assembles the data to be transmitted into unique packets and attaches a header to it, giving the source and destination addresses, a sequence number, and some error detection and correction information. The general format is shown in Fig. 9.11A.

The TCP packets then become the data that is assembled further into Internet packets (see Fig. 9.11B). The Internet protocol attaches a header giving source and destination addresses as well as other information about where and how the data is to be sent.

The IP header contains a 32-bit destination address identifying the location of the computer receiving the data. This 32-bit address is divided into four 8-bit segments. Each 8-bit segment is usually referred to by its binary equivalent. The result is the IP address. Every computer and most other devices have an IP address assigned by an organization set up for assigning and managing Internet addresses. You may have seen the address referred to in the format 51.78.23.189. This is called the *dotted decimal format*.

With a 32-bit address, over 4 billion individual computers and other devices can be assigned a unique address. However, we are already beginning to run out of addresses, and a new updated form of Internet protocol called IPv6 (Internet Protocol version 6) is gradually replacing it. It has a 128-bit address that provides billions and trillions of additional addresses so that even the smallest inconsequential device can have its own Internet address.

As the data is transmitted over the Internet, it passes through many devices referred to as *routers*. The router is the basic transmission control device of the Internet. What the router does is to examine all of the packets transmitted to it and to specifically look at their IP destination addresses. The router temporarily will store data being transmitted and then decide which part of the network it should be connected next to reach its desired destination. Routers store sets of information called *routing tables* that help the router decide the best transmission path through the Internet.

The data being transmitted ultimately reaches the NAP connected to the network where the destination exists. This may be a company, MAN, or LAN, or it could be an Internet service provider, such as the telephone company or cable TV company that will ultimately connect to the source computer. The source computer then strips away the TCP/IP headers to recover the original Sonet or Ethernet data.

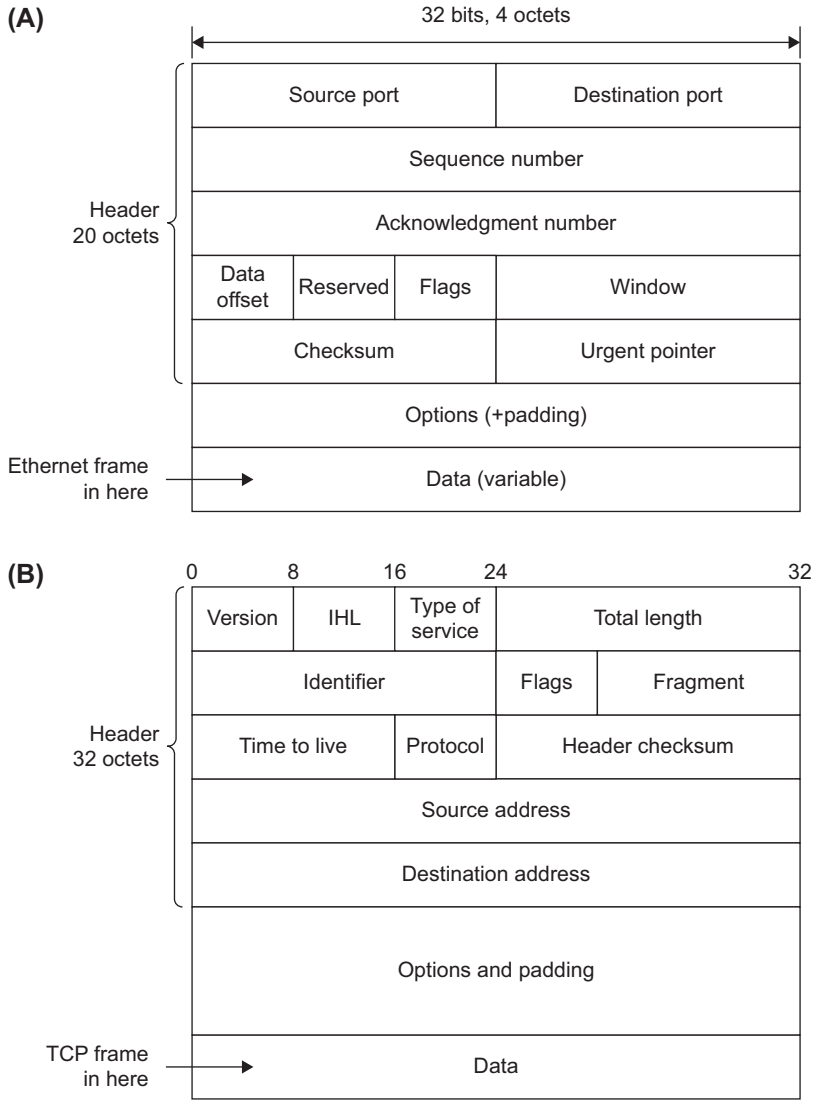


FIGURE 9.11 Protocols used in Internet. (A) Transmission control protocol (TCP). (B) Internet protocol (IP). The data in each frame are transmitted from left to right and top to bottom.

WIRELESS NETWORKS

Wireless networks are usually LANs or PANs, but may also be MANs. Most wireless networks are short-range wireless connections that bring greater mobility as well as freedom from interconnecting cables to networking. Fig. 9.12

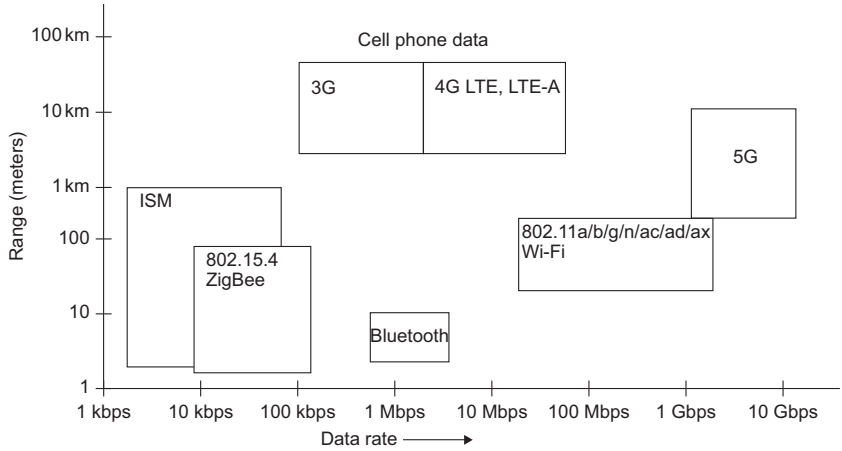


FIGURE 9.12 Summary of short-range wireless networking technologies shown as data rate versus range. See Fig. 9.12.

shows a graph designating the various types of wireless networking schemes in use today. In this graph, each networking technology is defined in terms of its data rate as well as its range. In this section, we take a look at all of these technologies, most of which you have heard of or already in use on a regular basis. The concepts of the Internet of Things (IoT) and machine-to-machine (M2M) communications are also introduced here.

Wi-Fi

Wi-Fi is one of the most widely used wireless networking technologies. Its trade name Wi-Fi, means *wireless fidelity*. This the name given to the IEEE's wireless Ethernet standard designated as 802.11. Wi-Fi was originally developed as a wireless extension to normal Ethernet LANs. It allowed laptops and personal computers and even cell phones to connect to a company or organizational LAN wirelessly instead of the normal CAT5 connection. This not only simplified and in many case eliminated new wiring but also gave employees greater freedom and mobility, particularly since most employees use laptop computers rather than fixed PCs. Today, Wi-Fi is the primary wireless link for tablets and smartphones to connect to the Internet.

Fig. 9.13 shows how Wi-Fi works. Each PC, laptop, or smartphone has a built-in data transceiver and antenna that communicate with a wireless access point (AP). This wireless AP is a transceiver that connects directly to an Ethernet switch, which, in turn, connects to the LAN wiring and its server. APs are placed at strategic locations within buildings to allow as many people as possible to connect wirelessly.

There are also public APs known as *hot spots*. These are present in coffee shops, airports, hotels, and in many other locations, allowing anyone with a

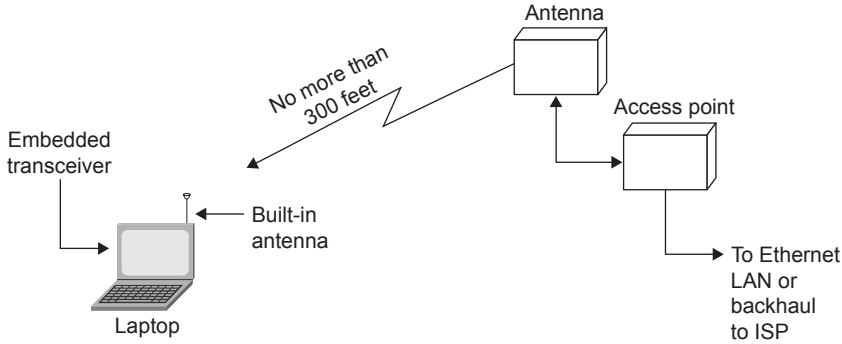


FIGURE 9.13 How a Wi-Fi access point or hot spot works.

laptop or cell phone to connect. These hot spots talk back to a central point by a backhaul method, such as a T1 telephone line or microwave relay link that connects to an Internet service provider that, in turn, is connected to the Internet.

The 802.11 standard exists in several basic forms. The original version of this standard is 802.11b. It operates in the 2.4- to 2.483-GHz unlicensed band. It uses the direct-sequence spread spectrum (DSSS) and is capable of data rates up to 11 Mbps in a range of up to 100 m. This frequency band is divided into 11 channels, each 22 MHz wide. The computer and AP decide on which channel to use to minimize interference with other transmissions. If you are close enough to the AP, you can actually get the 11-Mbps data rate, but if you are not, the system automatically ratchets down to 5.5, 2, or even 1 bps depending on the range, interference, and noise or other environmental conditions.

Another popular version of the standard is 802.11g. It is a faster version of Wi-Fi that also operates in the 2.4-GHz band. It can achieve data rates as high as 54 Mbps up to 100 m. It uses OFDM with 52 subcarriers.

Another variant of the standard is 802.11n, which uses OFDM and MIMO to achieve even higher data rates up to approximately 600 Mbps. Another less popular version is 802.11a, which uses the 5-GHz unlicensed band. It too uses OFDM and can achieve data rates to 54 Mbps. Even newer and faster versions are available. 802.11ac uses the 5 GHz band and can produce data speeds up to several Gbps under the most favorable conditions. It uses wider 80 and 160 MHz bands and higher-level 256-QAM modulation as well as increased MIMO configurations.

The 802.11ax version works in the 2.4 and 5 GHz bands and is even faster. It uses the wider bands of 802.11ac and 1024-QAM to produce even high rates to 7 Gbps. 802.11ax also uses multiuser MIMO to boost coverage range and data rate.

Faster data speed but over a shorter distance can be achieved with the 802.11ad, also known as WiGig. It operates in the unlicensed millimeter wave band from 57 to 64 GHz. The range is limited to about 10 m but a data rate to

7 Gbps is possible. Its most common use is video transport in consumer electronics gear.

Wi-Fi is also built into most of the new smartphones. While a smartphone has data capability because of its 4G LTE digital technology, Wi-Fi gives you one more way to access the Internet and email.

Wi-Fi is widely used throughout business and industry. It is also the most popular home networking technology. With no wires to install, it is easy to set up and use with a broadband DSL connection or cable TV access. Chances are you already have Wi-Fi in multiple forms.

Bluetooth

Bluetooth was developed as a PAN for connecting computers, cell phones, and other devices up to a range of about 30 feet. It is a low-speed data transmission method. Bluetooth operates in the same 2.4- to 2.483-GHz unlicensed spectrum as Wi-Fi. It uses a technique known as frequency-hopping spread spectrum (FHSS), where the data is divided into chunks and transmitted via a carrier that hops from one random frequency to another. Data is transmitted at a 1-Mbps rate using FSK. An enhanced data rate form of Bluetooth is also available to transmit at higher speeds up to 3 Mbps. The range is 10–50 m depending on the environment. The standard is managed by the Bluetooth Special Interest Group.

More recent versions of Bluetooth use a different form of FHSS and are designed to operate on less power. Called Bluetooth Low Energy (BLE) it is available in several forms for data rates of 1 or 2 Mbps. BLE nodes can operate for years from a single button cell because of the very low current drain. A newer version of BLE called Bluetooth 5 uses different modulation and coding schemes to achieve data rates to 2 Mbps over a longer range up to 50 m or more.

One of the basic features of Bluetooth is that it is capable of forming small networks called piconets. It does this by linking two Bluetooth devices together. One serves as a master controller, and it can connect to seven other Bluetooth slave devices. Once the PAN has been set up, the various connected devices can exchange information with one another through the master.

By far the most common application for Bluetooth is cordless headsets for smartphones. Other common uses are Bluetooth speakers for smartphones or tablets as well as hands-free systems in automobiles. But you will also encounter it in some wireless connections between a PC and a mouse or keyboard. Bluetooth may be the most widely used wireless standard in the world because it is used in so many smartphones, laptops, and other consumer equipment. Billions of Bluetooth chips have been sold.

ZigBee

ZigBee is another short-range PAN network technology with the IEEE designation 802.15.4. It uses low power, so the range is typically 100 m or less,

basically depending on the antennas and the physical environment where it is used. ZigBee also operates in that unlicensed spectrum from 2.4 to 2.483 GHz.

The IEEE 802.15.4 standard defines the basic radio technology. It usesDSSS and a version of QPSK that gives a data rate of 250 Kbps. The frequency spectrum is divided into 16 1-MHz channels.

The basic function for ZigBee is monitoring and control. Monitoring refers to telemetry that allows sensors to collect information, which is then transmitted by radio to some central collection point. It also allows for remote control of the devices such as lights, motors, and other items. The ZigBee Alliance, the organization that promotes and enhances this wireless technology, has developed a series of applications for industrial monitoring and control, home monitoring and control, energy monitoring (automatic meter reading) and control, and several others.

A major feature of the ZigBee technology is its ability to perform mesh networks. While a typical ZigBee radio node may only have a range of 30 m or less, the range can be extended by simply transmitting data from one node to another in a mesh network that may cover hundreds of meters, or in some cases even miles. A mesh is shown in Fig. 9.14. Each circuit is a ZigBee transceiver node, and each line is a wireless path. Mesh networks have many different paths for data and, therefore, are extremely reliable. If one path is blocked or disabled, data can usually find its way to the desired destination by way of another path. For example, in Fig. 9.14, a direct path may be from A-D-F-I-K, but if the D-to-F link is blocked or the I node is disabled, the mesh would automatically reroute the data through another path such as A-D-G-J-K.

Another application of the 802.15.4 standard is the replacement of the some IR TV remote controls. A radio frequency (RF) version called RF4CE is gradually replacing IR remotes in consumer electronic equipment providing longer range and no line of sight limitations.

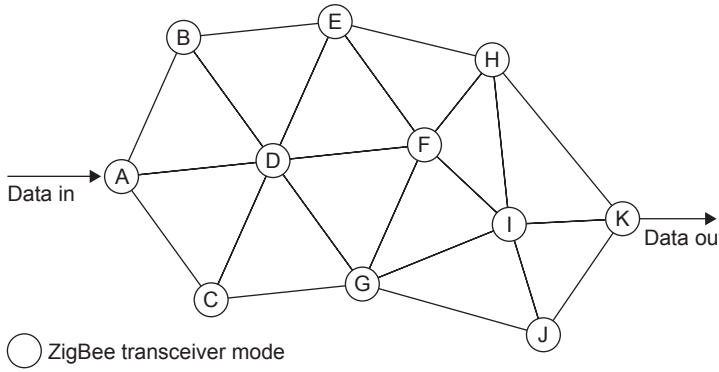


FIGURE 9.14 A mesh network can extend the overall range of a node and provide greater reliability through multiple possible paths. Most wireless mesh networks are ZigBee, but other wireless technologies may be used (e.g., Wi-Fi).

ISM-Band Radios

The industrial–scientific–medical (ISM) band has been mentioned before. This comprises a group of frequencies or bands set aside for unlicensed data transmission over short ranges. The main application is telemetry monitoring and remote control. The US frequencies are 13.56, 315, 433, and 902–928 MHz, with 915 MHz the most common. In Europe, 868 MHz is an unlicensed frequency. Transmitters and receivers are tiny single ICs or modules with power levels from about 1 mW to 1 W. Modulation is usually ASK/OOK or FSK. Data rates are low from a few kbps to usually no more than 100 kbps.

Some typical applications are garage door openers, remote keyless entry for vehicles, remote thermometers, medical telemetry, remote-controlled toy cars and boats, and sensor reading in industrial applications. Range is no more than a hundred feet or so, but longer ranges to several miles can be achieved with higher antennas.

Radio Frequency Identification and Near-Field Communications

Radio frequency identification (RFID) is a very short-range technology that is intended to substitute for standard bar codes. Practically everything has a printed bar code on it today so that with optical scanners the device can be recognized by a particular part number or other information that identifies it. The bar code readers are normally attached to a computer and, in turn, a network.

RFID devices are small thin plastic tags containing a radio chip that can be read by a wireless reader. The RFID chip contains an EEPROM memory in which is stored the device's unique identification number and other related information. A key characteristic of the RFID tag is that it contains no power source such as a battery. Yet it is designed to transmit its digital code to some external reading device whenever it is interrogated. Fig. 9.15 shows how it works.

The interrogation takes place when an external reader made up of a transmitter (TX) sends an RF signal to the nearby tag. The RF energy received by the tag's antenna is then rectified and filtered into a DC voltage that is used to power up the memory and the modulator circuit that sends data back to the reader. The reader also contains a receiver (RX) that picks up the small signal from the tag and sends it on to a computer where identification takes place.

RFID tags are generally used for what is known as asset tracking. RFID tags are attached to any relatively expensive item whose position is to be monitored, tracked, or otherwise controlled. It is good for keeping track of capital equipment, baggage, manufacturing tools, and other items. It is also used for personnel security on badges that employees wear and is good for animal tracking. One of the most widely used applications is automatic toll collection on highways.

RFID tags come in a variety of sizes, shapes, and technologies. Some of the older tags work at a frequency of 125 kHz or 13.56 MHz. The newer tags work

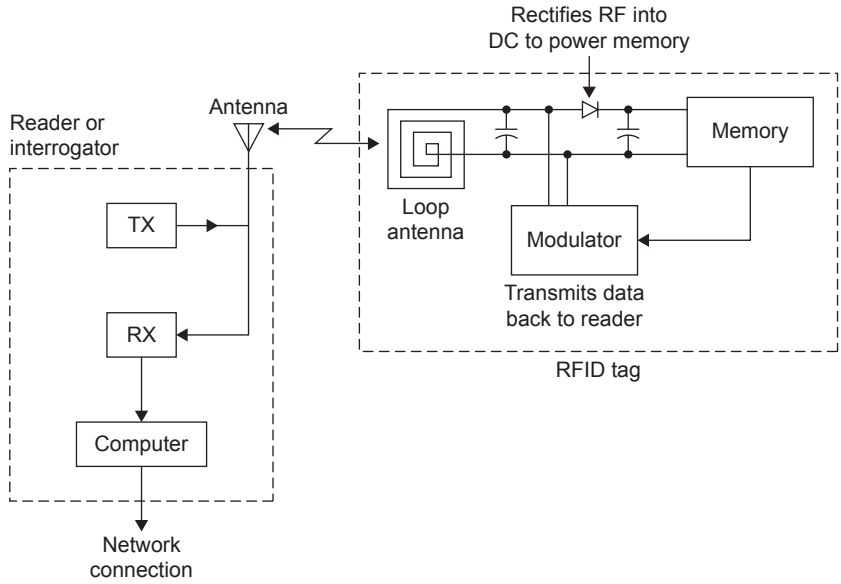


FIGURE 9.15 How RFID works. The tag has no power of its own but gets power from the transmitter in the reader.

at UHF frequencies in the 902- to 928-MHz range. All of these tags are passive devices with no power other than that received from the reader. Some longer-range RFID tags with small batteries have also been developed.

The unique code stored in the EEPROM is stored during the tag's manufacture. It is then clocked out at a relatively slow rate of speed around 70 kbps. The serial binary data is used in a form of amplitude modulation called backscatter modulation that produces minor variations in the reader's signal amplitude that can be converted back into a binary code.

Another similar RFID-like technology is known as near-field communications (NFC). It has an even shorter range of only about 1 foot. It operates on 13.56 MHz. It is mainly designed to be used in credit cards and in smartphones to produce automatic transactions such as credit card purchases, payment for transportation (e.g., train, subway, bus), or access to some facility.

BROADBAND TECHNOLOGY

Whenever you hear the term "broadband," it generally refers to a high-speed interconnection or Internet access. Most broadband systems provide data rates from roughly 1 to 100 Mbps, depending on the level of service purchased. Such broadband services are usually provided by cable TV companies or telephone carriers. Other organizations also offer various other types of Internet connectivity.

Cable TV Connectivity

Most cable TV companies offer high-speed Internet connectivity services. What they do is allocate one or more of the 6-MHz wide channels on the cable to this service (see Chapter 11 on TV). By using QPSK, 16-QAM, or 64-QAM, a wide range of customers can be offered multiple levels of Internet connectivity service. The customer gets a cable TV modem that connects to the cable along with the TV set. This modem provides the connectivity to a computer via Ethernet. A Wi-Fi AP is often connected to the cable modem to provide wireless connections to the Internet for PCs and laptops.

Digital Subscriber Lines

Digital subscriber lines (DSLs) are high-speed Internet connections that use standard telephone lines. DSL uses the standard twisted-pair telephone lines that come into every home for normal telephone service. These lines, because they were developed only for voice signals, are restricted in bandwidth and data rate. However, special techniques have been developed to allow very high-speed data transmissions on them. DSLs, also referred to as *asymmetric digital subscriber lines* (ADSLs), use a variation of OFDM called *discrete multitone*. What it does is to divide the restricted bandwidth of the twisted-pair cable into multiple OFDM channels, each 4 kHz wide. Then the data to be transmitted is divided into parallel paths and modulated using some form of QAM. All of this is handled by a DSL modem connected to subscribers' computers and the home telephone lines.

The speed potential of an ADSL line depends on how far away the subscriber is from the central office. The greater the distance, the lower the data rate. For even the longest runs from 12,000 to 18,000 feet, data rates of up to about 2 Mbps are possible.

Newer versions of ADSL have also been developed to permit data rates of up to about 12 Mbps at a range of 8000 feet and 20 Mbps at a range of about 4000 feet. Another version referred to as video digital subscriber lines or VDSLs extends the bandwidth further and uses higher-level versions of QAM to get data rates of up to 52 Mbps. A later version called VDSL2 can achieve up to 200 Mb/s over less than 2000 feet. The overall deliverable rate depends on the distance from the subscriber's modem to the neighborhood AP called a digital subscriber line access multiplexer (DSLAM). The Internet service provider (ISP) usually runs a fiber optic cable to the DSLAM and then connects via the existing telephone cable to the homes.

The newest form of DSL is called G.fast. Its main feature is that it can deliver combined download/upload speeds of up to 1 Gb/s over existing telephone wiring. G.fast achieves higher speeds by locating the distribution point unit closer to the home. The 1 Gb/s rate is usually achieved at a range less than about 70 m. Cable length is generally restricted to a maximum of 250 m. G.fast

uses time division duplexing rather than frequency division duplexing of most DSL versions. For that reason, the total data rate of 1 Gbps is the combined rates of download and upload speeds. An example is a mix of 800 Mb/s down and 200 Mb/s up.

Wireless Broadband

Wireless broadband services provide Internet connectivity via some wireless technology. Such services are provided by operating companies that service small towns and rural areas not served by standard telecom or cable TV companies. Such services usually provide fixed wireless data services with data rates in the 1–5 Mbps range. Wireless modems are connected to consumer computers that access nearby base stations within several miles.

The beauty of wireless broadband is that no cables or other hard connectivity is required. These are easy to set up, although at microwave frequencies, range is a problem as are multipath problems with buildings, trees, and other obstructions. However, with high enough antennas and sufficient power, wireless broadband has proved to be practical. Wireless broadband is growing rapidly, particularly in those areas where DSL and cable TV services are not currently available. An early application of the forthcoming fifth-generation (5G) cellular service is expected to be broadband access. Do not forget that wireless Internet connectivity can also be achieved by using the regular cell phone networks. You can purchase a data modem that plugs into your laptop or PC USB connector. This modem connects you just as it would a cell phone to your cellular network. You can also use your smartphone as a Wi-Fi hot spot. From there you can use your normal 4G LTE service to connect to the Internet, access email, or perform other networking operations. One of the first applications of the 5G NR technology is fast wireless broadband service.

THE INTERNET OF THINGS

The IoT is a movement that proposes to interconnect electrical or mechanical "things" to the Internet for the purpose of monitoring and/or controlling them. IoT, sometimes called the Internet of Everything, indicates how devices, machines, appliances, and other apparatus can communicate with humans or with one another to achieve some benefit or convenience. The IoT movement is well under way with billions of things already connected. Some sources predict that as many as 50 billion or more devices will be connected in the coming years.

There are two major segments of IoT, industrial and consumer. Industrial applications are particularly useful as it provides a way to monitor machines in a factory or systems in a process control plant. Sensors are used to keep track of environmental and physical conditions. Sensor data such as temperature, light level, pressure, mechanical position, and other factors are collected and sent via the Internet to a server that collects the data. Software then analyzes the

data to extract meaningful knowledge so that sound decisions can be made about machine maintenance or production efficiency. In addition to monitoring conditions, the IoT can be used to control things such as motors, lighting, or machine tools.

Other uses of industrial IoT include the smart grid that monitors home and business electrical usage by way of wireless electric meters. Monitoring and control of city street lighting is another. An older variation of IoT called M2M (machine-to-machine) uses wireless nodes to monitor fleet trucks or cars and their location by Wi-Fi or cellular.

Consumer applications of IoT also implement monitoring and control functions but in the home or automobile. Today, applications are everywhere. Smart fitness watches monitor things such as heart rate, steps taken, or other physical attributes of the wearer. These are usually transmitted by Bluetooth to a smartphone and perhaps then on to the Internet for storage and analysis by some computer. The result is a record of a person's training and physical conditioning.

Another consumer application is a video camera monitoring a home for security purposes. The camera transmits its observations by Wi-Fi to the Internet and then to a server that connects to a smartphone with the appropriate app where the video is viewed. Other examples are the monitoring and setting of a home thermostat, lighting, or security system over the Internet via a smartphone app. Voice control of products is one more use. Voice recognition software packages such as Apple's Siri, Amazon's Alexa, Google's Assistant, or Microsoft's Cortana are being incorporated into a wide range of Internet-connected products that seek information, answer questions, play music, or initiate some action. The possibilities are endless, it seems, and there are many more to come.

How Internet of Things Works

Fig. 9.16 shows the basic IoT system. In industry, sensors are used to monitor all manner of physical conditions. The sensor is part of a wireless network node that wirelessly transmits its data to a nearby gateway. ZigBee is one widely used wireless technology in industry. The gateway receives the ZigBee data and translates into packets suitable for transmission over the Internet. The gateway connects to the Internet cloud by way of an ISP. The collected data goes to a remote server where it is then routed to a storage system and/or a computer where it is analyzed and consumed by some user.

The approach in consumer IoT is similar. Items to be monitored or controlled contain a wireless sensor or actuator node. Wi-Fi is often used although Bluetooth is also popular. The nodes connect to a consumer gateway that interfaces to the Internet by way of a cable, DSL, or fiber ISP. In many homes the ISP Wi-Fi router serves as the gateway. As with industrial IoT, the data eventually goes to a server where it is the routed to some appropriate destination where data storage or analysis takes place.

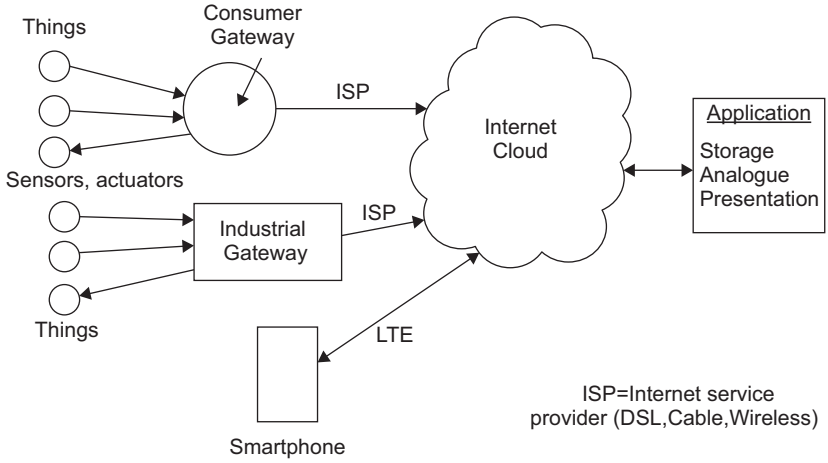


FIGURE 9.16 How the Internet of Things systems works.

In an M2M application, the sensor or actuator node uses cellular wireless to connect to the Internet and then the storage and analysis center by way of the existing cellular network. Smartphones are also widely used at both ends of IoT or M2M connection.

Wireless Technologies of Internet of Things and Machine 2 Machine

Wi-Fi and Bluetooth are by far the most often used short-range wireless links for IoT. However, many others are also used. Table 9.3 summarizes the most popular of these standards. The IEEE 802.15.4 standard is the base for ZigBee and Thread and several others not listed. ZigBee is used in both consumer and industrial spaces. Z-Wave and Thread are typically consumer-only technologies. Sigfox and LoRa are mainly industrial standards. A growing trend is the increased use of cellular for IoT connectivity especially in business and industrial applications. Standard 2G and 3G systems have been used, but the movement is to use simpler, less expensive, and more constrained versions of LTE such as LTE M1 and NB-IoT. Most of these standards use the unlicensed 2.4 GHz band. Others use the below 1 GHz bands, either cellular or ISM bands. There are lots of choices and no interoperability or compatibility between them. That may be a problem as it creates the need for multitechnology gateways if nodes are to exchange information.

The Issues of Internet of Things

The lack of a single wireless standard may be a challenge in both consumer and industrial applications. If possible, users should select one desired standard and

TABLE 9.3 A Summary of the Most Commonly Used IoT Short-Range Wireless Technologies

Standard	Frequency (GHz)	Maximum Rate	Modulation	Maximum Range	Application
IEEE 802.15.4	2.4	250 kbps	DSSS, O-QPSK	100 m	Consumer, industrial
Wi-Fi 802.11a/b/g/n/ac/ax	2.4 and 5.8	11 Mbps–7 Gbps	DSSS, OFDM	200 m	Consumer. Commercial, industrial
Bluetooth 4.x, 5	2.4	2 Mbps	FHSS, GFSK	50 m	Consumer
ZigBee	2.4	250 kbps	DSSS, O-QPSK	100 m	Consumer, industrial
Z-Wave	Sub-1	100 kbps	FSK	30 m	Consumer
Sigfox	Sub-1	600 bps	GFSK, DBPSK	1 km+	Industrial
LoRa	Sub-1	50 kbps	SS chirp	1 km+	Industrial
LTE-M1	Sub-1	1 Mbps	OFDM	1 km+	Industrial
NB-IoT	Sub-1	250 kbps	OFDM	1 km+	Consumer, industrial

use it for everything. Next, be aware of privacy and security problems. Hackers can disrupt a network or steal data or do other more nefarious mischief. While most standards now include encryption and authentication capability, be aware that more advanced methods may be necessary to prevent hacking. Finally, realize that billions of sensors will generate a massive amount of data that has to be stored somewhere. Furthermore, the data is of little use until it is processed, analyzed, and presented. This will require significant storage and computing capability if IoT is to be useful.

Project 9.1

Become More Familiar With Wireless Data Protocols

You may want to find more information on the most popular short-range wireless data methods. The following websites are recommended. And you may want to do a general Internet search with Bing, Google, or Yahoo!

Wi-Fi: www.wi-fi.org
Bluetooth: www.bluetooth.com and www.bluetooth.org
ZigBee: www.zigbee.org
The Wikipedia entries are also quite good.

Chapter 10

Audio Electronics

Digital Voice and Music Dominate

In this Chapter:

- Sound and the electronics that deliver it.
- Digital audio.
- The compact disc (CD).
- Voice and music electronics.
- Wireless audio
- Streaming audio

INTRODUCTION

While the telephone, telegraph, and radio are generally considered the first real electronic applications, audio was certainly next. By "audio," I mean sound: voice and music, things we can hear. Audio signals have frequencies within the range of the human ear. Over the years many electronic devices have been developed to amplify, capture, and reproduce sounds of all types. Today, like everything else in electronics, audio electronics is predominantly digital, although many analog devices and systems are still in use. This chapter is a summary of audio devices you know and use every day including stereo systems, iPods, wireless speakers, and streaming audio.

THE NATURE OF SOUND

Sound is just pressure waves in the air that your ear can hear. Anything that produces a noise or other disturbance produces pressure waves that travel to your ears where the sound waves are converted into signals that your brain recognizes as sound. The frequency range of these air vibrations is 20 Hz–20 kHz. Our ears do not respond to lower or higher frequencies even though they may be present. Human hearing also varies widely due to age and health status. Age brings on hearing loss, especially of the higher frequencies.

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00010-2
Copyright © 2018 Elsevier Inc. All rights reserved.

There are four key things needed in audio electronics:

- The ability to convert sound waves into electrical signals.
- The means to convert the electrical signals into sound.
- A way to amplify and reproduce the signals.
- Media to store or record the signals.

This is what audio electronics is all about.

Microphones

The microphone is the transducer that converts sound waves into an analog signal. The sound waves impinge on the microphone, and it causes vibrations that are translated into a signal by either capacitive element or an inductive coil. A technical discussion about microphones is way beyond the scope of this book. In any case, the resulting signal is usually very small, in the millivolt range or even microvolt range. Therefore, it must usually be amplified before it is useful. This is the function of a small-signal amplifier usually called a *preamplifier*. What you do with the signal after that is up to you. Typically it will be amplified further for use in a public address or other sound system. Or alternately, the voice may be recorded. Many voice signals will be used in a telephone, cordless, or cellular.

Speakers

A speaker is a transducer that converts the audio signal into sound waves that you can hear. You have obviously seen a speaker, so little explanation is needed. Its main element is a paper or plastic cone that vibrates at the audio frequencies applied to it. Then it produces the sound pressure waves that our ears will hear.

Fig. 10.1 shows how a speaker works. The cone is attached to a form around which a coil of wire is wound. This is the so-called *voice coil*. That voice coil is

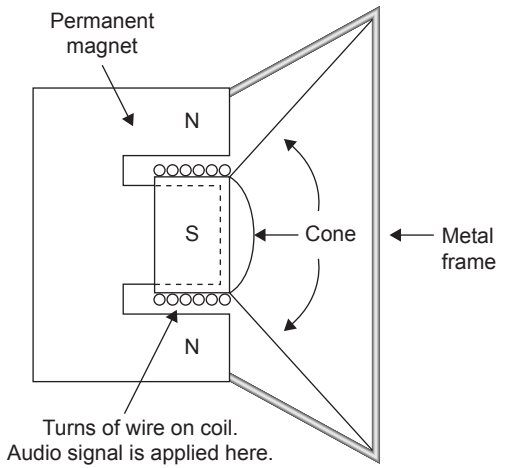


FIGURE 10.1 Cross section of speaker showing major components and how it works.

positioned inside a strong permanent magnet with north and south poles. Now when you apply the audio signal to the coil, current flows and causes the coil to become an electromagnet. The electromagnet generates alternating north and south poles as the voice or music signal occurs. These magnetic fields interact with the permanent magnet, causing attraction and repulsion of the voice coil, and the cone moves. The motion of the cone accurately reproduces the original sound waves.

Speakers come in a wide range of sizes and types. Cone speakers are usually called midrange speakers in which they can reproduce most of the frequency range except for the very low and very high frequencies. Special speakers are used for those frequencies. A woofer or subwoofer is a larger speaker designed for frequencies of about 600 Hz and below. A tweeter is a special speaker optimized for the higher frequencies above 10 kHz. Special filters called *crossover networks* separate the signal into low, mid, and high frequencies as shown in Fig. 10.2.

The remainder of this chapter addresses the amplification and recording or storage of audio signals. Along the way, most analog audio signals are digitized. And many are also compressed to save storage space or reduce the binary data rate for transmission.

DIGITAL AUDIO

The sounds we hear and the sounds we generate are analog signals. A microphone picks up the voice and music and produces an analog signal to be amplified or stored. We have amplifiers and speakers that will accurately reproduce the sounds. But the real challenge with audio is capturing, storing, or recording

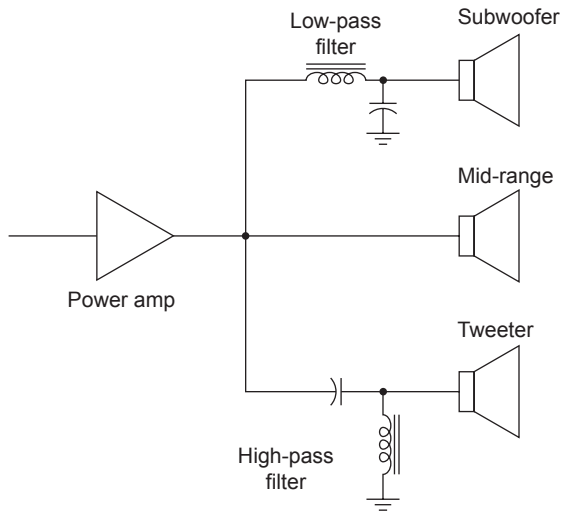


FIGURE 10.2 Cross over networks keep signals of different frequencies separate for appropriate speakers.

the sounds for later reproduction. With today's digital techniques, we can store not only voice and music more accurately than before, but we can also transmit it more easily by radio, TV, or the Internet.

Past Recording Media

Edison invented the phonograph in 1877. This was the first device ever conceived to record voice. A microphone converted the sound into vibrations that moved a sharp needle in direct accordance with the sound. The needle cut a varying groove in the wax coating on a rotating cylinder. Later, a needle placed in the groove moved the diaphragm in a horn speaker that translated the movement into sound. The quality was poor but it worked, and the concept was soon translated into what we know as a *phonograph record*. The record disc is rotated while a needle cuts a spiral groove into the plastic that accurately captures the sound. To reproduce the sound the disc is rotated at the same speed and a needle is placed in the groove to reproduce the sound in a speaker. A transducer converts the movement of the needle in the groove into an analog signal that is amplified.

Early records spun at a speed of 78 rpm and could only hold a few minutes of sound. Later a smaller 45-rpm record was invented to play minutes of music at a lower cost. Then a larger long-playing record spinning at only $33^1/_3$ rpm was produced that could hold an hour or so of sound. Stereo or two channel sound was also effectively recorded into a V-shaped groove in the record.

Records were soon upstaged by magnetic tape. A plastic such as Mylar was coated with a powdered iron or ferrite magnetic material. The music or sound was then applied to a magnetic coil that put a magnetic pattern on the tape representing the sound. A coil passed near the tape would convert the magnetic pattern variations into a small voltage to recover the sound. Reel-to-reel tape was popular for a while, but magnetic tape became the recording media of choice for years when the Philips cassette tape was invented. Other formats like the ever-popular 8-track unit were also used.

All of these formats worked well but had their limitations. Record grooves wore out with usage causing the high-frequency response to be eroded. Scratches and dirt on the record also produced noise. As for tape, it had good frequency response but had its own noise that could not be reduced below a certain level. The dynamic range of both was poor.

Digital technology has solved all these problems. Now the most popular medium is the compact disc (CD), which records sound in full digital format. It has very low, practically undetectable noise, wide frequency response, and a very long life. The cost is also low.

Digital sound is also routinely stored in computer memories like flash EEPROMs and transmitted over the Internet. With digital techniques, sound can also be processed with digital signal processing (DSP) such as compression, filtering, and equalization.

Dynamic Range

Dynamic range refers to the difference between the highest and lowest volumes of sound that a system can handle. It is a measure of how wide an amplitude range a particular storage media can record or an audio system can accommodate. It is also a way to state the maximum sound pressures that our ears can withstand and the lowest levels that we can hear.

The upper level of amplitude is set by our ears and the level at which distortion occurs. The lowest levels of the dynamic range are determined by the noise in the system. Noise is the random voltage variation caused by thermal agitation of electronics in electronic components and random variations in the magnetism on a magnetic tape or disc. As the volume of a sound gets lower at some point, it will be smaller than any noise present and not distinguishable from the noise background.

In general, the wider the dynamic range the better. It usually means lower noise and greater volume (loudness) to better match the range of human hearing.

Dynamic range can be stated in terms of power or voltage. It is usually a very wide range, so we resort to a unique mathematical method to express it. The term decibel (dB) refers to how dynamic range is presented. In math form you take the ratio of the maximum and minimum voltage, take the logarithm of that, and multiply by 20:

$$dB = 20 \log (V_{max}/V_{min})$$

For power,

$$dB = 10 \log (P_{max}/P_{min})$$

The dynamic range of a typical phonograph record is probably about 50 dB, and magnetic tape, about 55 dB. But a CD is approximately 90 dB, the best we have.

Dynamic range can be improved by lowering the noise in a system. This can be done with special signal-processing techniques. The most notable are methods produced by Dolby.

Digitizing Sound

Most digital sound and music is digitized with a sampling rate of 44.1 or 48 kHz. Recall the Nyquist requirement that to capture and retain the frequency content accurately, the analog signal has to be sampled at least twice the highest frequency of the sound. Since most music and the human ear cutoff at about 20 kHz, then any sampling rate greater than 2 kHz × 20 kHz = 40 kHz will satisfy that requirement. The rate of 44.1 kHz was standardized for CDs and 48 kHz for professional recordings. At 44.1 kHz, a sample is taken every 1/44,100 = 22.676 μs.

Fig. 10.3 shows the sampling of an analog signal. The smooth curve is the analog music or voice. At each vertical interval a sample is taken. In this example, a 4-bit ADC is used so there are $2^4 = 16$ possible levels. Note the 4-bit code associated with each sample amplitude. The binary samples are stored

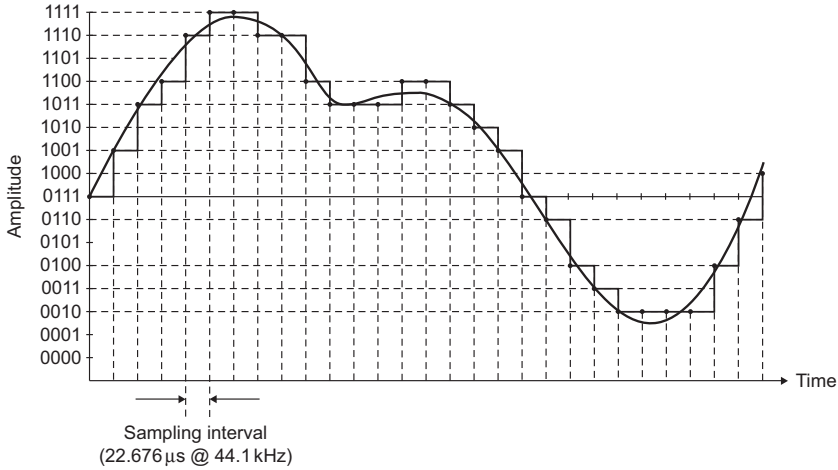


FIGURE 10.3 How audio signal is digitized. In this example, each sample is assigned a 4-bit code. The stepped approximation shown is what a DAC would deliver to the speakers.

for later playback. When sent to a DAC, the samples will reproduce the audio in a stepped approximation shown overlaid with the analog signal. Some low-pass filtering of that signal will produce a sound which almost duplicates the original.

Digitizing audio usually results in each sample producing a 16-bit word. With 16 bits you can represent 2^{16} = 65,536 levels. That produces a dynamic range from the highest to lowest amplitude levels of 65,536 to 1. On the decibel (dB) scale, that is a range of 96 dB—far greater than any dynamic range of previous analog recording methods. And noise is virtually nonexistent. It is so low no one can hear it. The overall result is a highly accurate way to capture sound and music. The 16-bit words can then be conveniently stored in a memory or captured on a compact disc.

Digital Compression

Digital compression is a mathematical technique that greatly reduces the size of a digital word or bitstream so that it may be transmitted faster or stored in a smaller memory. Digitizing sound creates a huge number of bits. Assume stereo music that sampled at a rate of 44.1 kHz to create 16-bit words for each sample. One second of stereo music, then, produces 41,000 × 16 × 2 = 1,411,200 bits. A 3-min song is 60 × 3 = 180 s long. The result is 1,411,200 × 180 = 254,016,000 bits. Since there are 8 bits per byte, the result is 31,742,000 bytes or nearly 32 MB or megabytes. That is an enormous amount of memory for just one song. With a recording medium like the CD with a storage capacity of about 700 MB, that is okay. But for computers or portable music devices, it is impractical, not to

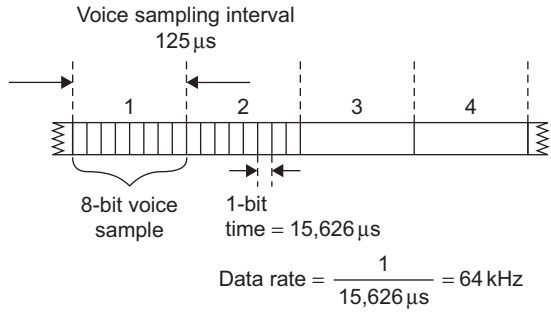


FIGURE 10.4 Voice signals up to 4 kHz for the telephone are sampled at an 8-kHz rate, producing an 8-bit sample, each 125 µs. Stringing the samples together in a serial data stream produces a digital signal at a 64-kHz rate.

mention expensive. And to transmit that over the Internet would take about 4 min at a 1 Mb/s rate. Pretty slow by today's standards.

The solution to this storage and transmission problem is to compress the bitstream into fewer bits. This is done by a variety of mathematical algorithms that greatly reduce the number of bits without materially affecting the quality of the sound. The process is called *digital compression*. The music is compressed before it is stored or transmitted. Then it has to be decompressed to hear the original sound.

The two most commonly used music compression algorithms are MP3 and AAC. MP3 is short for MPEG-1 Audio Layer 3, the algorithm developed by the Motion Picture Experts Group as part of a system that compressed video as well as audio. AAC means advanced audio coding. MP3 is by far the most widely used for storing music in MP3 music players and sending music over the Internet. AAC is used in the Apple iPod and iPhone and used on the iTunes site to send music. It is also part of later MPEG-2 and MPEG-4 video compression formats. Both methods significantly reduce the number of bits to roughly a 10th of their original size, greatly speeding up transmission and easing storage requirements. There are many more compression standards out there, but these are by far the most used and the ones you will most likely encounter.

To perform the compression process you actually need a special CPU or processor. It is typically a special DSP device programmed with the algorithm for either compressing or decompressing the audio.

There are also a number of compression methods used just for voice. Voice compression was created to produce signals for telephony. Most phone systems assume a maximum voice frequency of 4 kHz. The most common digitizing rate is twice that or 8 kHz. 8-bit samples are typical. If you digitize voice creating a stream of samples in serial format, the signal would look like that in Fig. 10.4. Each sample produces an 8-bit word where each bit is 125/8 = 15.625 µs long. That translates to a serial data rate of 1/15.625 µs = 64 kbps. This takes up too much bandwidth in a telephone system, so compression is used. The

International Telecommunications Union (ITU), an international standards organization, has created a whole family of compression standards. These are designated as G.711, G.723, G.729, and others. These mathematical algorithms reduce the bit rate for transmission to about 8 kbps. You will see them used in voice over Internet phone (VoIP) digital phones, which are gradually replacing regular old-style analog phones.

There are many other forms of audio compression. Another common one is Dolby Digital or AC-3 that is used in digital movie theater presentations and some DVD players.

How an MP3 Player Works

MP3 players such as the Apple iPod are amazing electronic systems in a hand-held package. They all take the general form shown in Fig. 10.5. At the heart of the player is a processor. It may be a general processor or a DSP. In some cases, two processors are used, one to control the player buttons, controls, and display, and other general housekeeping functions; a separate DSP handles the compression/decompression. A ROM holds the general control program for the device. A large flash EEPROM is used to store the music in compressed form. Some devices also provide for an external flash memory plug-in device to hold more music. A USB port is the main I/O interface to connect to a PC for the music downloads.

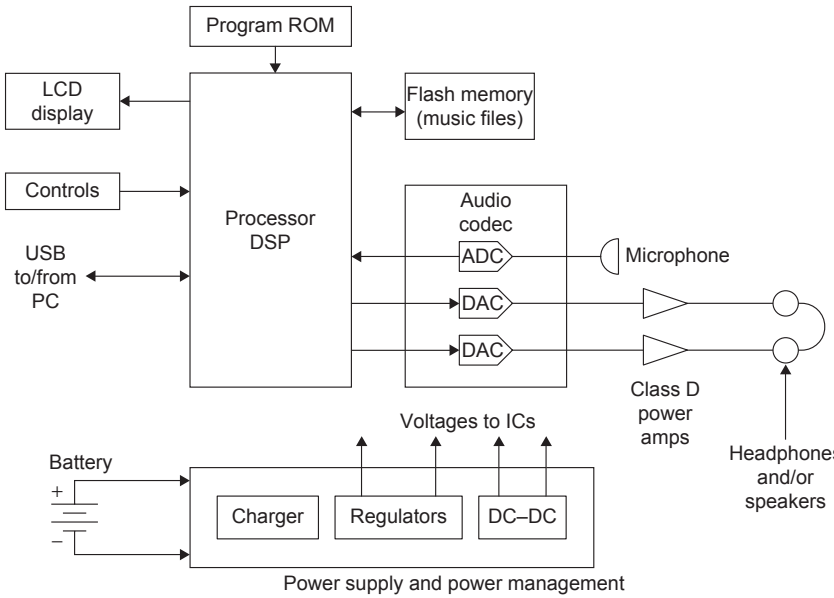


FIGURE 10.5 General block diagram of a digital music player like Zune MP3 or Apple iPod.

The codec in the device is the coder–decoder. This chip holds the ADC to digitize music from an external source such as a microphone (coder) and the DACs that decode or translate the decompressed audio back into the original analog music for amplification. Class-D switching power amplifiers are used for the headphones to reduce power consumption. One or more internal speakers may also be used. Other circuits include the LCD display and its drivers and LED backlights if used. A power management chip is normally used to provide multiple DC voltages to the different circuits and to manage power to conserve it. This section also contains the battery charger.

The Compact Disc

CD is by far the most popular digital audio medium in use today. It has been around since the 1980s and is still going strong. It has virtually totally replaced the Philips cassette magnetic tape cartridges and vinyl phonograph discs. About the only competition the CD has is from flash EEPROM devices such as those used to store MP3/AAC music for portable music players.

You have probably seen a CD. Let us add a little background so you will appreciate the CD. It is a 4.72-in. (120-mm) diameter disc made of plastic. It is about 0.05-in. (1.2-mm) thick and has a hole in the center for mounting on the motor that spins the disc. It is actually a sandwich of clear plastic and a thin metal layer for reflecting light.

The music is recorded on the disc in digital format. A laser actually burns *pits* into the plastic representing the 1's and 0's of the digital data (see Fig. 10.6). These pits are extremely small, about 0.5-μm wide (a micron designated μm is 1-millionth of a meter). The flat areas between the pits are called *lands*. A binary 1 occurs at a transition from a pit to a land or vice versa while the land is a string of binary 0's. The binary data is recorded as a continuous spiral track about 1.6-μm wide, starting at the center and working outward. That is a very efficient way to store the data, but it means that the motor speed must vary to ensure a steady bit rate when the music is played back. The pickup mechanism will experience higher speeds at the center of the disc and lower speeds at the outer edges of the disc, so that a speed control mechanism keeps the recovered data rate constant.

The music on a CD is derived from two stereo channels of music with a frequency response from 20 Hz to 20 kHz. Digitization occurs at the standard 44.1-kHz rate. Each sample is 16-bits long. The 16-bit words from the left and right channels are alternated and formatted into a serial data stream that occurs at a rate of $44.1\,\text{kHz} \times 16 \times 2 = 1.4112\,\text{MHz}$. The 16-bit words are then encoded in a special way. First, they undergo an error detection and correction encoding scheme using what is called *cross-interleaved Reed–Solomon code* (CIRC). This coding helps detect errors in reading the disc caused by dirt, scratches, or other distortion. The CIRC adds extra bits that are used to find the errors and fix them prior to playback.

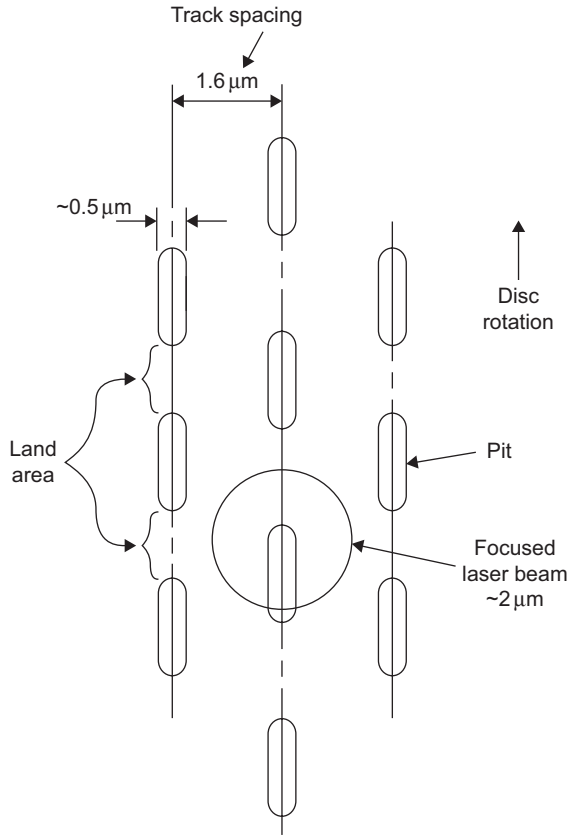


FIGURE 10.6 Digital music on a CD is encoded as pits and lands on the CD surface. These are burned in by a laser. A laser light shined on the pits and lands produces a reflection that a photodetector picks up to create the original digital data.

Next, the serial data string is then processed using what is called eight-to-fourteen modulation (EFM). Each 8-bit piece of data is translated into a 14-bit word by a lookup table. EFM formats the data for the pit-and-land encoding scheme. Finally, the completed data is formatted into frames 588-bits long and occurring at a rate of 4.32 Mbps. That is the speed of the serial data coming from the pickup assembly in a CD player before processing.

To recover the audio from the CD, the disc is put into the player and a motor rotates it. Refer to Fig. 10.7. A laser beam is shined on the disc as indicated in Fig. 10.6. The reflections from the pits and lands produce an optical light pattern that is picked up by a photodetector that converts the light variations into the 4.32-Mbps bitstream. A motor control system varies the speed of the motor to keep the data rate steady. The data stream goes to a batch of processing circuits. First, the EFM is removed, and then a CIRC decoder identifies and repairs

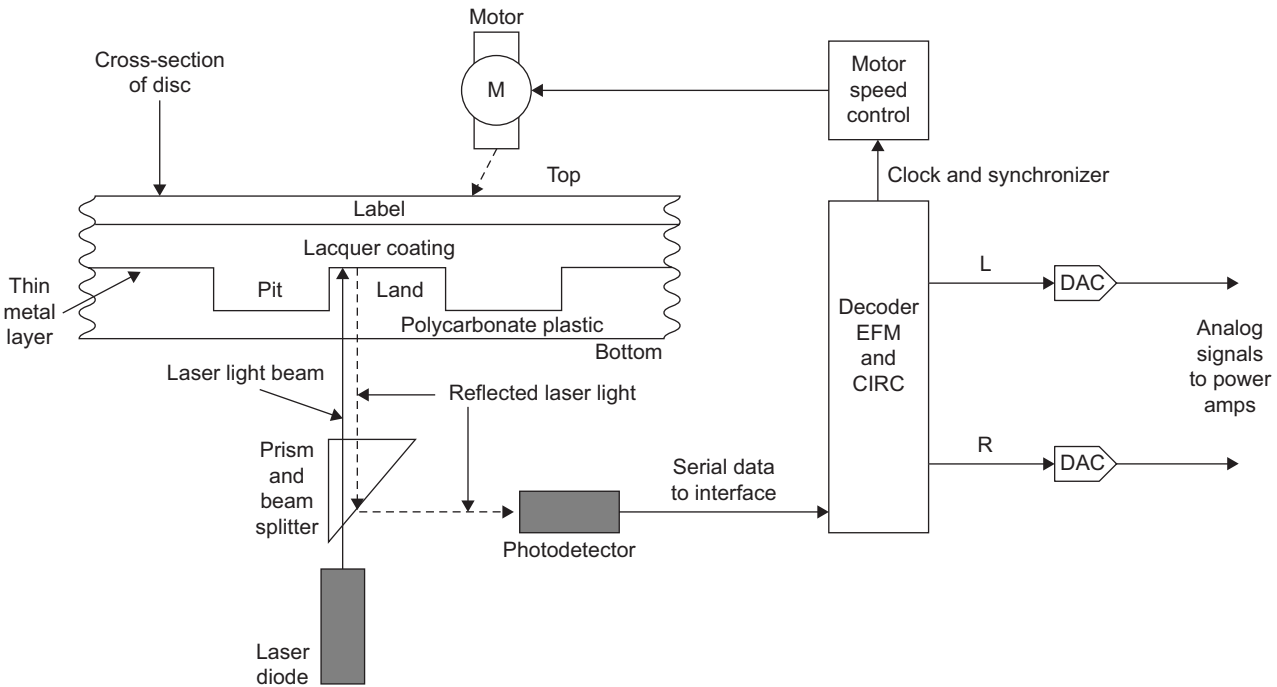


FIGURE 10.7 Block diagram of CD player.

any errors and recovers the original 1.41-Mbps data stream. A demultiplexer separates the left- and right-channel 16-bit words and sends them to the DACs, where the original analog music is recovered and sent to the power amplifiers and speakers.

The CD can store lots of data. Its capacity is in the 650- to 700-MB range. That translates into a maximum of about 74 min of audio. And this is not compressed.

AUDIO–VIDEO RECEIVER

An HDTV receiver is usually at the heart of most consumer electronics home entertainment systems. A secondary piece is the audio–video (AV) receiver, which provides the audio component of the entertainment. The systems usually include the CD player, several radio options, and all the audio power amplifiers that operate the multiple speakers. The AV receiver also accepts inputs from the TV set, DVD player, and other external devices to provide higher quality sound. This section provides a look at this piece of equipment and how it works.

Fig. 10.8 shows a general block diagram of the AV receiver. Note the multiple power amplifiers on the right. These drive the speakers that are part of a surround-sound system. Most of these are class AB linear amplifiers that deliver power levels from about 20 W per channel to over 100 W in the larger units. The frequency response is 20 Hz–20 kHz or more with a distortion level of 0.5%–0.9% or less.

The power amplifiers get their inputs from multiple sources. These sources include audio from the internal radio receivers and the CD player as well as many other external sources. These sources include the TV receiver, DVD player, VCR, and a cable or satellite box, as well as audio from older devices such as tape players and phonographs. Many receivers also accept inputs from an iPod or other MP3 music player. A large switching matrix is used to select the desired input. That selection can be made from the front panel controls or via the remote control.

Radio Choices

All AV receivers contain the traditional AM and FM analog radios. These are still popular sources of music. But more and more the most recent receivers contain one or more digital radio sources such as HD radio or satellite radio.

HD radio is becoming more popular each year. This is a digital radio broadcast option available at most US radio stations today. The AM and FM sources are digitized and broadcast on the same frequencies but with digital modulation techniques like orthogonal frequency division multiplex a wide separate channel is needed. The result is an improvement in the signal. Digital signals offer slightly better frequency response on both AM and FM. AM signals will sound

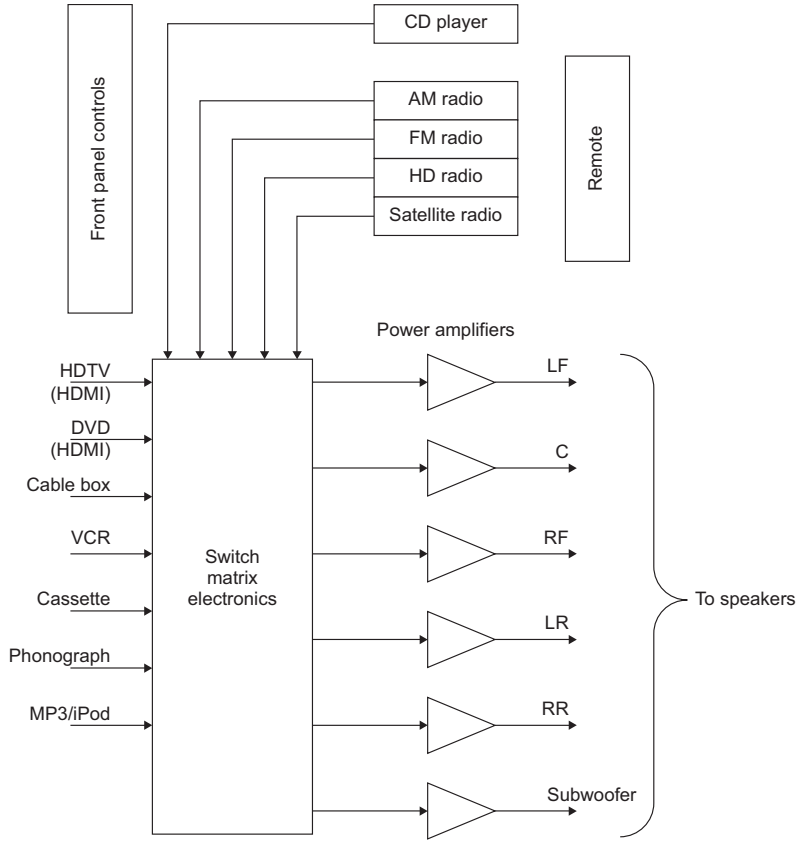


FIGURE 10.8 Block diagram of typical audio–video receiver, the heart of the audio reproduction part of a consumer home entertainment center.

more like FM, and FM signals will be nearly CD quality. Furthermore, the digital signals are more noise and fade free than the standard AM and FM signals. While HD radio was first made available in automobiles, it is now widely available for home use. Separate HD radios can be purchased at most consumer electronics stores. And more HD radios are being built into AV receivers.

Satellite radio was also first made popular in automobiles. Yet separate home receivers are available. Some AV receivers now include satellite radio capability. Satellite radio is available from one source, SiriusXM Radio. This is a subscription service with hundreds of radio, music, news, sports, and other channels. The signals are digital, delivering near CD-quality sound. The satellites use the 2.3-GHz microwave band. The main difficulty when using satellite radio at home is that an outside antenna is needed. Some radios supply a small antenna for window mounting so that the antenna can "see" the satellites in the sky. Otherwise, poor or no reception may occur.

Surround Sound

Virtually all audio sound today is stereo. That is, the music comes from at least two speakers, one on the left and one on the right. The sound is recorded as two separate channels with different microphones to provide a stereophonic experience to the listener. A minimal system uses two speakers but some add a subwoofer for good bass reproduction. This is sometimes referred to as a 2.1 stereo system, that is, two speakers and one subwoofer.

New audio systems offer surround sound. These systems feature six, seven, or eight speakers. The idea is to totally envelop the listener with sound as it might be heard in a concert hall or theater. There are speakers in front and at the rear. The first surround-sound implementations were analog but today most surround sound is fully digital. The most common surround-sound method is Dolby Digital 5.1, which uses five speakers and a subwoofer as shown in Fig. 10.9. These are left front (LF), right front (RF), center (C), left rear (LR), and right rear (RR). Then there is one subwoofer. The woofer can be positioned anywhere but is usually at the front. Each speaker is driven by its own amplifier in the AV receiver.

The big question that you may have is where do the six channels of sound come from? Not from the radio or a CD for sure, both of which are stereo only. In most cases, the sound signals will come from a DVD player. Right now it is about the only common source of 5.1 surround sound, although some HDTV programs support it. During recording of the original material, one microphone is used for each channel. The digitized audio for each of the channels is stored on the DVD.

Incidentally, there are more elaborate versions of surround sound. For example, 7.1 adds two more speakers on the left and right. As of now there are few, if any, 7.1 music sources available.

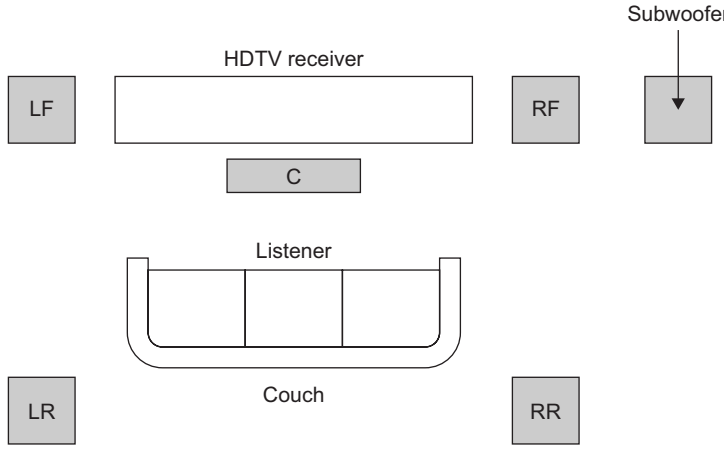


FIGURE 10.9 How 5.1 surround-sound system is set up.

When you play the DVD, the digital signals from each channel are sent to a special chip that decodes them and otherwise performs necessary noise reduction, equalization, and other operations. The recovered signals are then sent to DACs for conversion to their original analog format for amplification.

SPECIAL SOUND APPLICATIONS

When you think of audio or sound, you think mainly of voice or music reproduction. Yet, electronic sound is used in lots of additional places. Some interesting examples are in wireless audio, streaming music, musical instruments, sonar, ultrasound, and hearing aids.

Wireless Speakers and Headphones

A popular audio feature today is wireless speakers. Such speakers are powered by batteries or may be plugged into the AC mains. The audio connection is wireless commonly using the Bluetooth radio technology. Some newer systems use Wi-Fi for the wireless connection. Such speakers help to minimize the wiring mess in a home entertainment system. They also are popular for providing louder and better quality audio for smartphones and tablet/laptop computers. Bluetooth headphones are also a popular accessory for smartphones.

Downloading and Streaming Audio

While CDs are still as popular music medium, even more popular today is downloading music. Songs are selected from a music source such as Apple's iTunes and the compressed digital music file is downloaded via the Internet to an MP3 player or a smartphone. Music is usually purchased one song at a time and once downloaded it can be played.

Streaming audio is the term given to receiving audio mostly music over the Internet. The compressed music files are delivered in real time to a computer or smartphone and played directly. The streaming requires specific software that performs the transfer, memory buffering, decompression, and playing. The computer or smartphone and its software takes the music file into a buffer memory then parses it out continuously to the player. A wide range of streaming services are available such as iTunes Radio, Pandora, Spotify, Google Play, Beats, and others.

Musical Instruments

Musical instruments produce their own sounds, of course. Each has its own unique signature made up of the basic notes or tones to which are added the mix of harmonics or overtones unique to the physical structure of the instrument. Some instruments like horns and drums rarely need amplification. Other instruments like guitars and violins commonly need some amplification, especially

in large venues such as on stage addressing hundreds or thousands of people. Special microphone-like devices called pickups are used with string instruments. The pickup is usually one that converts the string vibrations into a small signal that is then amplified.

One of the most popular electronic instruments is the *synthesizer*. It has a keyboard like a piano. The keys are equivalent to those on a piano. Each key then triggers the electronics to generate a tone of the desired frequency. That tone is especially modified by DSP circuits to sound like that note played on a piano, an organ, or any other musical instrument. The DSP synthesizes or constructs the tones digitally and sends them to a DAC that converts them into the analog sound to be amplified.

Are Vacuum-Tube Amplifiers the Best Audio Amplifiers?

Vacuum tubes? I'm kidding, right? Actually, no. There are many audio experts, especially guitar players and some recording studio engineers, who still believe that vacuum-tube amplifiers are superior to solid-state amplifiers. And as it turns out, the largest market for general vacuum tubes today is guitar, high-end stereo, and recording studio amplifiers.

Contrary to popular belief, vacuum tubes did not really go away when transistors and integrated circuits came along. They are still widely used in China, Russia, and a few other countries. And that is where most tubes are made these days. Vacuum tubes are still widely used. Cathode ray tubes or picture tubes are still at the heart of many TV sets and computer video monitors. Magnetrons are vacuum tubes that are in every microwave oven. And microwave vacuum tubes, such as traveling-wave tubes and klystrons, are still used in high-power microwave transmitters. And vacuum-tube audio amplifiers.

Why are vacuum-tube amplifiers so popular still? It is the unique sound they produce. It is a sound that musicians appreciate and want in their sound mix. And the sound is difficult and expensive to reproduce in a solid-state amplifier. The sound is smoother and less harsh. The sound is "warmer," and the compression that such amplifiers produce when overloaded is exactly what makes rock and country music sound like it does. It looks like vacuum tubes will be around much longer, but prices are sky high and some tube models are hard to find.

Noise-Canceling Earphones

You have probably heard of these or maybe seen or used them. They make clever use of analog signal processing to greatly minimize surrounding noise when you are trying to listen to music with headphones.

First, most of these headphones try to isolate the actual headphone from the surroundings with a tight-fitting ear bud or soft foam pads around the earphone that limit the amount of external noise getting to your eardrum. This is called *passive noise control*.

Second, each earphone contains a built-in microphone that picks up the surrounding noise. It amplifies it then inverts it in phase. The original noise from the microphone is then added to the inverted noise. Being the same but exactly out of phase with one another, the two noise signals cancel one another. The cancellation is not perfect, but the noise reduction is significant. It can greatly minimize noise on a plane or in a car or other types of noisy environments.

Sonar

Sonar means sound navigation and ranging. It is basically the underwater equivalent of radar. It is used on ships and submarines for making depth measurements, detecting underwater objects, and for warfare. The two types of sonar are passive and active.

Passive sonar is simply the idea of putting underwater microphones called *hydrophones* on a long wire or arrays of such microphones in the water to listen for any sounds that occur. Amplifiers boost the signal levels and various filters help sift through all the complex signals that can be heard. In military applications, the sounds are digitized and various DSP programs help filter and identify specific sounds. Many ships create unique sounds called signatures that can be digitized and stored for comparison to any sounds picked up for positive identification. The sounds include fish and other sea life, boat and ship engines, motion through the water by a ship or boat, or any noise that occurs inside a submarine. Sound travels very easily through water so is easy to pick up. With practice and experience, a sonar operator can identify almost everything occurring over a wide range around the microphone array.

The other form of sonar is *active*. This is like radar where a high-frequency pulse of sound is applied to a transducer to convert the pulse into sound waves for transmission through the water. The frequency of the pulse is usually ultrasonic, that is, above most human hearing. Frequencies from about 15 kHz to 1 MHz are used, depending on the application. The pulse of sound travels out from the transducer and is then reflected off distant objects. The reflections go back to the source where they are picked up by a microphone. Then, knowing the speed of sound transmission in water, the distance to the object can be computed. Sonar depth sounders point the transducer downward to get a measure of the distance to the bottom. Sonars can easily pick up reflections from ships miles away for navigation safety purposes or for military actions.

Hearing Aids

Electronic hearing aids have been around a long time. The older analog types were large and cumbersome but worked fine. Integrated circuits made them much smaller and more acceptable to the hearing impaired. Today, the newer hearing aids use digital technology. The microphone picks up the sound and amplifies it, then digitizes the sound in an ADC. A DAC can then translate the

sound back into audio for amplification and application to the earphone. Most digital hearing aids now incorporate DSP filters. These filters may be customized to the frequency response of the ear, correcting for different frequencies. Mostly the high-frequency response is lost due to aging. Using an external computer, each hearing aid can be adjusted from volume and frequency response to fit the exact deficiency.

Project 10.1

Experience Digital Radio

Digital radio in the United States is available from satellites and via the existing AM and FM analog stations through HD radio. Both offer commercial free music and other content in multiple channels. HD radio is free but satellite radio is a pay-for-listen service.

In the United States, two satellite radio services were established in the early 2000s, XM Radio and Sirius Radio. The two services merged to form Sirius XM Satellite Radio. Both offer subscription services to music, news, sports, and other information. Both services operate in the 2.3-GHz band, and get their signals from satellites. Special receivers and antennas are required.

Satellite radio is a digital service and both systems used compressed audio for signal transmission. HD radio is simultaneously broadcast with existing AM and FM analog signals. A special receiver is needed to receive it. The digital techniques greatly improve sound quality.

A good project if you are a music lover is to try one or both of these services. You can get an HD or satellite radio for your vehicle or you can buy a home unit. Some high-end AV receivers have one or the other in addition to the traditional AM and FM radios. You can purchase home desktop units from Best Buy and other electronics dealers for a reasonable price.

HD radio is free and you will find that some stations transmit additional digital channels not available in analog form. These give you more music genres. No special antenna is needed.

To learn more about HD radio, do a Bing, Google, or Yahoo! search. Also go directly to the website of the company that invented HD radio, iBiquity (www.ibiquity.com), for more details.

You can also buy a satellite radio from several local sources. But you will need to subscribe. Go to www.siriusxm.com.

Project 10.2

Test Your Hearing Response

To check the frequency response of your ears, go to www.audiocheck.net/audiotests_frequencycheckhigh.php. There are a few online audio tests for your hearing. This website has a whole batch of other audio response tests that you may be interested in.

Chapter 11

Video Technology

TV and Video Is All Digital Now

In this Chapter:

- How scanning works to create video.
- Basic color TV principles.
- US and other standards for digital and high-definition TV.
- How a digital TV set works.
- TV screen technologies.
- Cable TV.
- Satellite TV.
- Over-the-Top TV
- Cell phone TV.
- DVD players.
- Virtual reality.

INTRODUCTION

Nothing in electronics has affected us more than the development of television. Okay, I have not forgotten the PC and the Internet, which have also seriously impacted our lives. But TV came first and has been working its magic on us for far longer. The impact of television or video on our lives is significant in that we spend more than half of our waking hours in front of a video screen, either watching TV or working with a video monitor on a computer. And, of course, you also interact with the liquid crystal display (LCD) screens on smartphones, laptops, smart watches, and personal navigation devices. The social and political impact has been enormous. For this reason it helps to understand a little bit about how video works. Video is perhaps one of the most complex segments of electronics, but this chapter helps make those fundamentals easy to understand.

VIDEO FUNDAMENTALS FOR THE IMPATIENT

The main feature of any video device is the screen. The first video or TV screens were cathode ray tubes (CRTs), and those are still around in some older TV sets

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00011-4
Copyright © 2018 Elsevier Inc. All rights reserved.

and computer monitors. The most commonly used TV and video screen today is the LCD. LCD screens are used in the newer TV sets and in most personal computers. They are also used in laptops, smartphones, personal navigation devices, and anything else that has a screen on it. Some older TV sets also use plasma, digital light processing (DLP) projection technology, and other methods to display very large pictures. Now newer screens use light-emitting diodes (LEDs). There is more detail on TV screens later in this chapter, but for now, the most important part of understanding video is to learn the methodology used to create and present video regardless of the screen type.

A video system is a method for converting a picture or scene into an electronic signal that can be transmitted by radio or cable or stored electronically. Some type of device is needed to take in the light and color information from a picture or scene and convert it into an electrical signal. Once in electrical form, the video can be modulated onto a radio carrier for transmission or electronically stored. The process of converting the scene or picture into an electrical signal is known as scanning.

Scanning Fundamentals

A video signal is usually generated by a video camera. The camera takes the scene and scans it electronically, dividing it into hundreds or even thousands of very thin horizontal lines (see Fig. 11.1).

The horizontal scan lines comprise a sequence of light and color variations. The camera produces an analog signal whose frequency and amplitude vary with the brightness and color changes along the scan line. The whole idea in video is to transmit the video signal one scan line at a time at very high speeds. If you are not transmitting the signal by radio or cable, you can store it, such as recording it on a computer hard drive or magnetic tape. In any case, the received signals are then converted back into scan lines and applied to the screen by scanning the lines across the receiving screen very fast from left to right and top to bottom.

The secret to producing a high-quality video picture is to use enough scan lines with enough detail in each, so that the color, brightness, and fine detail in the picture are retained. Note in Fig. 11.1 that the analog signal for one scanned line is such that the higher-amplitude voltages are closer to black, while the lower-amplitude signals are closer to the white level. This is what a scan line from a monochrome or black-and-white (B&W) video system produces. It is called the *brightness* or *Y signal*. Color will be covered later.

Aspect Ratio

When talking about TV screens, the key factors are size and aspect ratio. The *size* is usually the diagonal measure of the screen in inches. The *aspect ratio* is the ratio of the picture width to the picture height. Standard TV sets and video

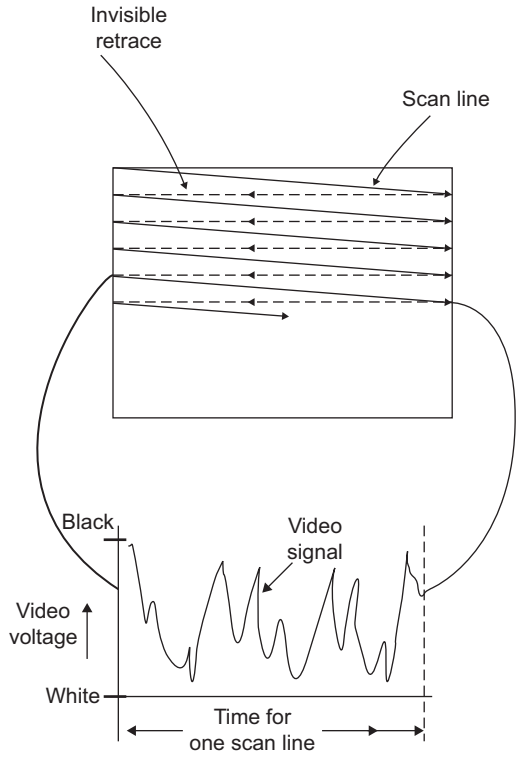


FIGURE 11.1 How scanning converts a scene of light and color into an electronic signal.

monitors previously used an aspect ratio of 4:3 as shown in Fig. 11.2. Most of the newer TV screens and video monitors have an aspect ratio of 16:9. This wider format was chosen because it is a better fit with the wide-screen movie formats.

Persistence of Vision

When you think about it, it just does not seem possible that a complete picture or scene can be reproduced in electronic format by scanning. The scanning process just breaks the picture or scene down into hundreds or perhaps thousands of scan line signals, and the only way that a picture can be created is for those scan lines to occur at a very high rate of speed. Luckily, this technique works because we all have a visual characteristic known as persistence of vision. Persistence is that characteristic of the eye that prevents it from following very high-speed changes in light variations. In other words, if the scan lines are traced across the screen at a very high rate of speed, your eye simply cannot follow them one at a time but instead puts the whole thing together and sees a single steady picture. If you scan at too low rate, you will actually begin to see the scan lines, and your eye will interpret this as a kind of flicker.

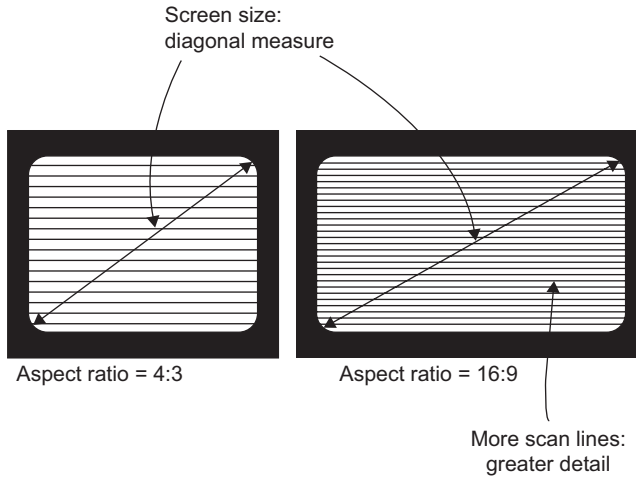


FIGURE 11.2 TV screen size and aspect ratio.

The concept of persistence of vision has been known for decades. Motion picture films take advantage of this characteristic of our eyes as well. Remember that movies are just a high-speed sequence of individual still pictures recorded on film. If you can get the frame rate up to a level of approximately 24 frames per second or faster, your eye will translate the changes from one still frame to the next as motion.

Analog TV

As you may know, the Federal Communications Commission eliminated analog TV broadcasts in the United States as of June 12, 2009. But while analog TV has been replaced by digital TV (DTV), that does not mean that it is not still around. You will still find analog TV in many other countries of the world, and it is also still used in closed-circuit television. In any case, it is such a widely used standard that understanding it is useful.

Back in the late 1940s and early 1950s, the United States created what is called the National Television Standards Committee (NTSC) TV standard. It basically specifies that a picture is made up of 525 horizontal scan lines, known as a video *frame*. As it turns out, one frame is actually made up of two fields of 262.5 scan lines. The scene or picture is first scanned 262.5 times from top to bottom, creating one field. This field is then transmitted at a rate of 60 fields per second. Then the scene is scanned again with another 262.5 lines, and these are transmitted next. The second field is interlaced with the first field to form the complete 525-line picture. See Fig. 11.3. The result is that you will see 30 complete 525-line frames per second. This is fast enough for persistence of vision to work nicely. The interlacing helps significantly in reducing any perceived flicker.

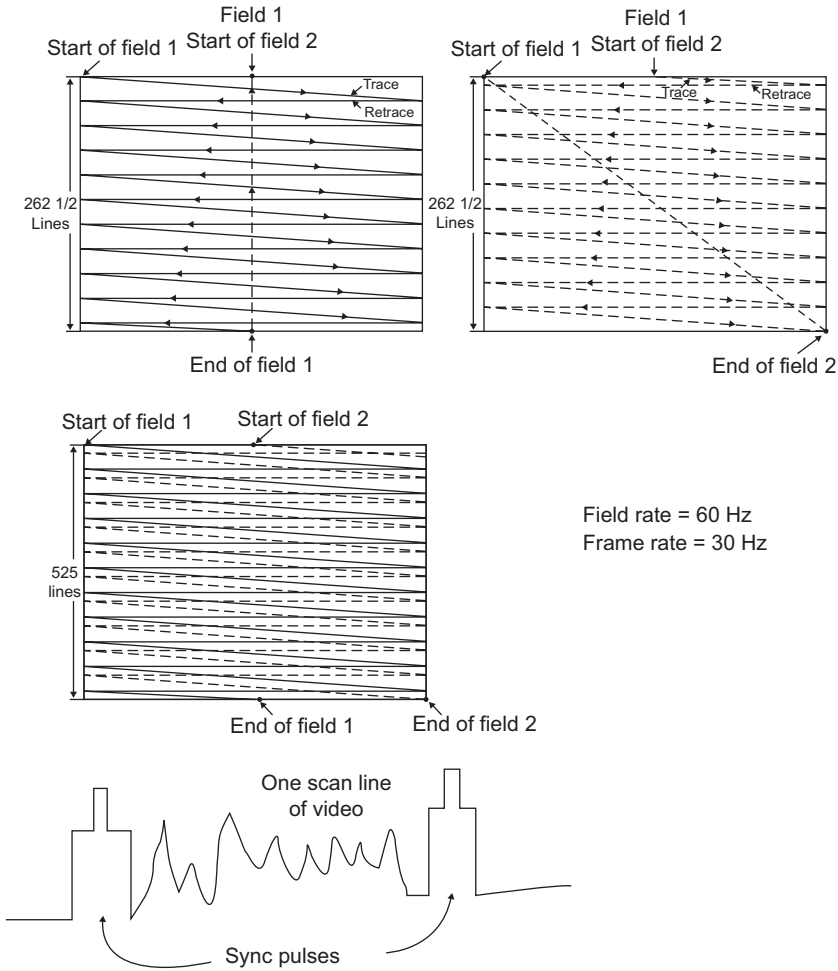


FIGURE 11.3 Interlaced scanning helps reduce flicker. Sync pulses help keep the receiver and transmitter in step with one another.

One thing that you may be wondering is how do you keep the TV receiver screen in step with the video camera or other video source? This is solved by creating synchronizing pulses that are transmitted before and after each scan line (see Fig. 11.3). After one field is scanned, a larger group of synchronizing pulses occurs between fields to cause the receiver to start the scanning back at the top again. The synchronizing pulses are transmitted or stored along with the analog video signal for each line. These synchronizing pulses are then used to trigger the receiver's circuitry to make sure that the scene is sequenced properly on the screen.

Other World TV Systems

The US NTSC analog system is used in Canada, Mexico, and Japan. But other analog systems are used throughout the world. In Europe, specifically the UK, Germany, Italy, and Spain, the PAL (phase alternation line) standard is used. It uses 625 scan lines with a frame rate of 25 frames per second. In France and in some other countries, a system called SECAM for Sequenteil Couleur a Memorie (or sequential chrominance and memory) is used. It too uses 625 scan lines and a 25-frame-per-second rate. PAL and SECAM systems have a better vertical resolution for picture detail because of the greater number of scan lines, giving a perceptibly improved picture over the NTSC system. Most of the other countries of the world have adopted one of these three systems. However, now the United States and most of Europe have digital systems.

Digital TV

Most TV and video now is transmitted and stored in digital or binary format. Scanning is still the process used to convert the scene into an electrical signal, in this case a stream of binary numbers representing the brightness and color detail. Each scan line is still essentially an analog signal but that is converted into a sequence of binary numbers by an analog-to-digital converter (ADC). The basic process is illustrated in Fig. 11.4. The ADC samples are measures of the analog signal at a constant rate, as shown by the dots along the curve in Fig. 11.4. Remember that to retain the information in an analog signal when it is converted into digital, the signal must be sampled at a rate at least twice as fast as the highest-frequency signal contained in the analog signal. Since video signals contain extremely high frequencies, the sampling rate is very fast. Most video contains scene details with frequencies beyond 4 MHz. That means a sampling rate of at least 8 MHz to capture the detail. In any case, each sample results in an 8-bit binary number. These bytes, one representing each of the sequential samples, are sent one after another in a serial binary data stream as shown. The video data can then be transmitted or stored.

Each of the binary numbers produced by sampling produces what we call a *pixel* or picture element. This particular binary number will ultimately translate to a specific analog voltage value and produce a specific brightness level along the scan line.

One way to visualize a digital video display is to think of it as an array, or horizontal scan lines, each made up of a sequence of pixels (see Fig. 11.5). Each pixel is a dot of light or, in this case, a square. That pixel is derived from a specific binary number developed during the scanning and sampling process. Each of those pixels represents a specific brightness level from white to black. A digital-to-analog converter (DAC) converts the binary brightness value back into a specific shade of gray.

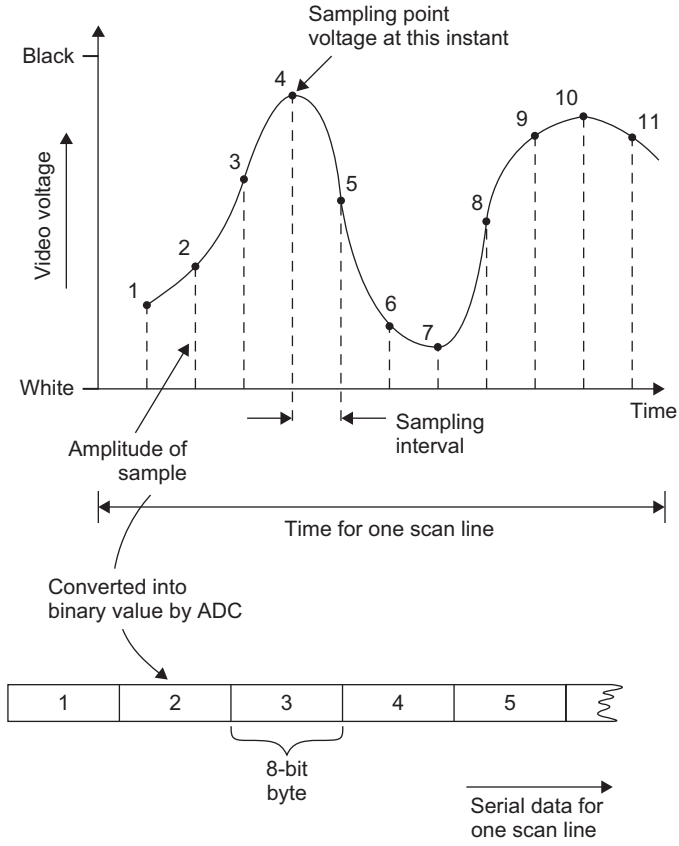


FIGURE 11.4 Digital TV is created by digitizing the analog video signals with an ADC, and then converting it into a serial bitstream of video data words.

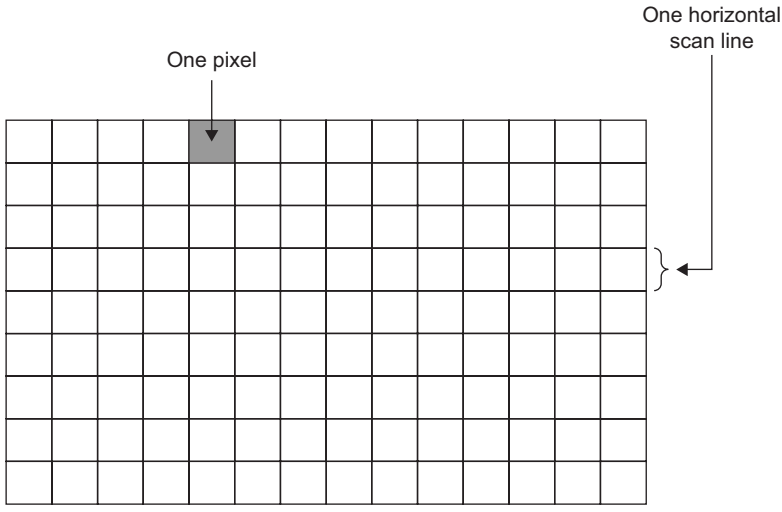


FIGURE 11.5 TV screens can be thought of as thousands of rows and columns of pixels, each represented by data.

DTV uses the interlaced scanning principles described earlier to help minimize flicker. But it also uses a faster progressive scan. This is where each scan line making up the screen is scanned sequentially one after the other from top to bottom. To minimize flicker, *progressive scanning* must be done at a higher rate of speed than interlace scanning. Progressive scanning is used simply because it creates a sequence of digital numbers that is more conveniently stored and processed one after the other than in a two-step interlaced process.

DTV uses a variety of different formats. In the basic format, it produces 480 scan lines with 640 pixels per line. This is roughly the equivalent of what you would see with an analog TV signal. This is what we call the DTV standard resolution format. Both interlaced and progressive scanning formats can be used with rates of 24, 30, and 60 frames per second.

Picture Resolution

One thing that you should understand about video is the concept of resolution. This refers to how much fine detail you can see on the screen. In analog TV, brightness and color detail results in very-high-frequency analog signals. The older original analog TV was limited to frequencies of approximately 4.2 MHz. Modern HDTV uses much higher-frequency responses up to about 10 MHz. To see that picture detail, you must transmit the analog signal over a channel that has sufficient bandwidth. Most radio channels and cable systems have bandwidth limitations and essentially act as a low-pass filter that will remove some of the higher frequencies. While you will still see a picture, it will lack some of the fine detail that your eye may or may not notice.

Resolution as it relates to DTV is a combination of how many scan lines plus how many pixels per line are used. Obviously, the greater the number of scan lines and the greater the number of pixels, the more detail you are going to be able to transmit and ultimately see.

A higher-resolution format to produce what we call high-definition (HD) TV uses 720 scan lines with 1280 pixels per line. The HD format uses 1080 horizontal lines with 1920 pixels per line. Both of those HD formats can use either interlace or progressive scanning at rates of 30, 60, 120, and 240 frames per second. Just remember that the frame rate simply refers to the number of times per second that each frame is presented on the screen. The earlier slow frame rates of 30 and 60 frames per second often produce a kind of picture smearing when the scenes are changing at a high rate of speed. This is noticeable in action movies or in sports events. The newer 120- and 240-frames-per-second scan rates essentially eliminate this problem.

The newest form of DTV is called ultrahigh definition (UHD). Other designations are UHD-1, Quad TV, or 4K. The 4K is derived from the pixel format of 3840×2160 where there are almost 4000 (4K) lines with 2160 pixels each. The

resolution is four times the standard HD resolution. The scan is progressive at 50 or 60 frames per second. The resolution is astonishing and fine detail can easily be seen. 4K TV sets have been available for a few years, but prices are still very high. 4K resolution content is not yet widely available but there is some 4K over-the-air (OTA) broadcasts and some 4K movies on DVD.

Another term you will hear associated with 4K is HDR or high dynamic range. HDR is a feature that offers better picture contrast meaning whiter whites, darker blacks, and a wider range of colors. Not all 4K TV sets have HDR but those that do deliver amazing picture quality.

Also now available are 8K screens with a resolution of 7680 lines with 4320 pixels per line. It is meant primarily for the very large screens (>85 in.). Frame rate is 60 Hz and 8K is usually accompanied by HDR.

Color Video Principles

Thus far, the signals we have described are what we call monochrome or B&W video. In *monochrome video*, all we capture and transmit and reproduce is the brightness variations along a scan line that range from black to white and an infinite number of shades of gray in between. But, of course, today most video is color. Capturing, transmitting, processing, and displaying color is a far more complex process than monochrome.

One physics principle that makes color video possible is the concept that any color of light can be reproduced by simply mixing the right combination of red, green, and blue light. Take a look at Fig. 11.6. Mixing red and green creates yellow. Mixing red and blue produces violet (magenta), while mixing green and blue produces the color cyan. In any case, as it turns out virtually, any color can be created using just the right mix and intensities of red, green, and blue.

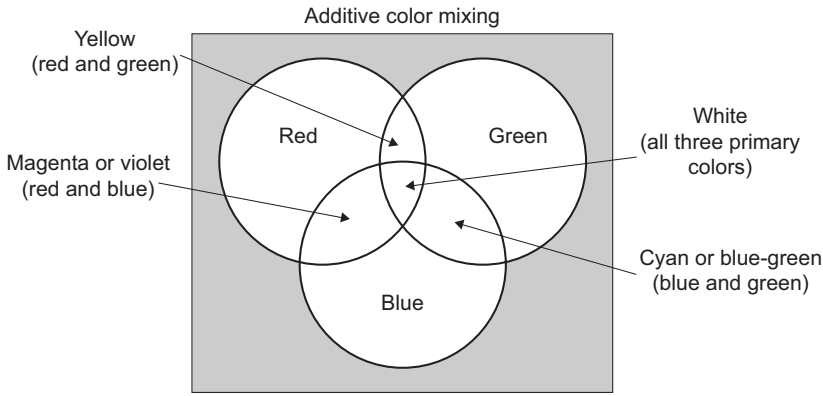


FIGURE 11.6 Any color of light can be reproduced by mixing red, green, and blue light in the right proportion.

Strangely enough, there is one unique combination of the three colors that creates white. Black is produced, of course, by just turning off all the light sources. The color TV problem is how do you capture the individual colors and then how do you reproduce them?

Video cameras use a light-sensitive imaging chip called a CMOS imager or charge-coupled device (CCD). An optical lens focuses the scene on the chip. The chip itself is made up of millions of tiny light-sensitive elements that are charged like a capacitor with a voltage depending on the brightness level reaching them. The analog video signal for a scan line is then created by sampling those light-sensitive elements one at a time horizontally. The result is an analog signal whose amplitude is proportional to the light level. The result is a B&W brightness or Y signal.

Fig. 11.7 shows how the color signals are produced. The scene is actually passed through a lens and a beam splitter that divides the scene into three identical segments. Each is passed through individual red, green, and blue filters. Three light-sensitive imaging chips then produce three separate analog signals for the red, green, and blue elements in a scene. The red, green, and blue analog signals are then individually amplified and sampled by an ADC to translate them into a binary sequence. The three binary streams are then transmitted serially as a sequence of red, green, and blue for each picture element on the imaging chip. Each of these RGB colors will then later form a pixel on the viewing screen.

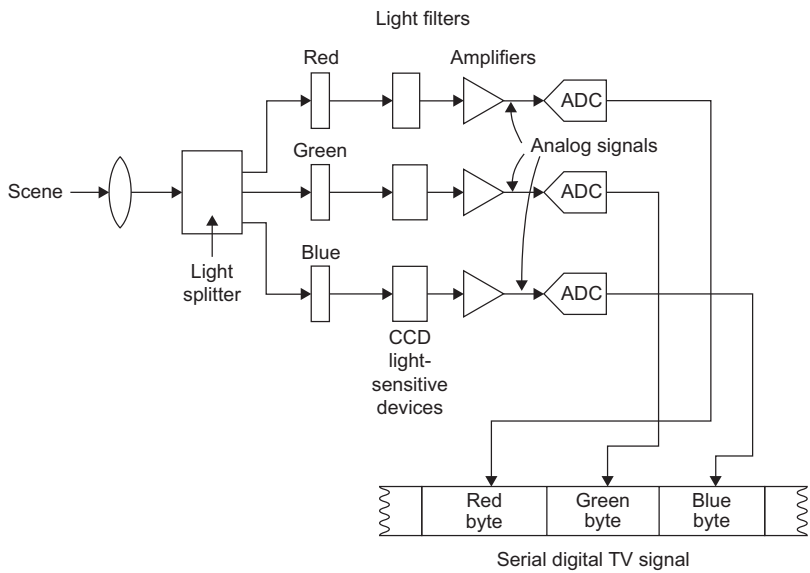


FIGURE 11.7 Red, green, and blue digital color signals are generated by filtering the scene into its red, green, and blue components, and then digitizing the resulting analog signals.

Video Compression

Generating a color video signal produces a serial bitstream that varies at a rate of hundreds of millions of bits per second. Consider these calculations:

- For each pixel, there are three color signals of 8 bits each making a total of $8 \times 3 = 24$ bits per pixel.
- For a standard DTV screen, there are 480 lines of 640 pixels for a total of 307,200 pixels per frame or screen.
- For one full screen or frame, there are $307{,}200 \times 24 = 7{,}372{,}800$ bits.
- If we want to display 60 frames per second, then the transmission rate is $7{,}372{,}800 \times 60 = 442{,}368{,}000$ bits per second, or 442.368 Mbps. That is extremely high frequency.
- To store one frame of video of this format, you would need a memory with 55,296,000 bytes or 55.296 MB. And that is just one frame.
- To store 1 min of video you would need a memory of 3,317,760,000 bytes or just over 3.3 gigabytes (GB). And that is just 1 min. Multiply by 60 to get the amount of memory for an hour.

Imagine the speeds and memory requirements for 1080p or a 120 frames-per-second format. And we have not even factored in the stereo audio digital signals that go along with this. Anyway, you are probably getting the picture here. First, data rates of 442.368 Mbps are not impossible, but they are impractical as they require too much bandwidth over the air and on a cable. And they are expensive. Furthermore, while memory devices such as CDs and DVDs are available to store huge amounts of data, they are still not capable of those figures. Therefore, when it comes to transmitting and storing digital video information, some technique must be used to reduce the speed of that digital signal and the amount of data that it produces.

This problem is handled by a digital technique known as *compression*. Digital compression is essentially a mathematical algorithm that takes the individual color pixel binary numbers and processes them in such a way as to reduce the total number of bits representing the color information. The whole compression process is way beyond the scope of this book, but suffice it to say that it is a technique that works well and produces a bitstream at a much lower rate. And, the compressed video will take up less storage in a computer memory chip.

The digital compression technique used in DTV is known as MPEG-2. MPEG refers to the Motion Picture Experts Group, an organization that develops video compression and other video standards. Another standard is MPEG-4 AVC. For 4K and 8K a compression method called high efficiency video coding is used.

What you have to think about when you consider the transmission of digital video from one place to another is that it is typically accompanied by audio. The audio is also in serial digital format. Those digital words will be transmitted along with the video digital words to create a complete TV signal.

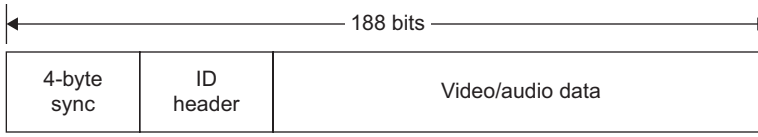


FIGURE 11.8 HDTV packet for ATSC US digital color TV system.

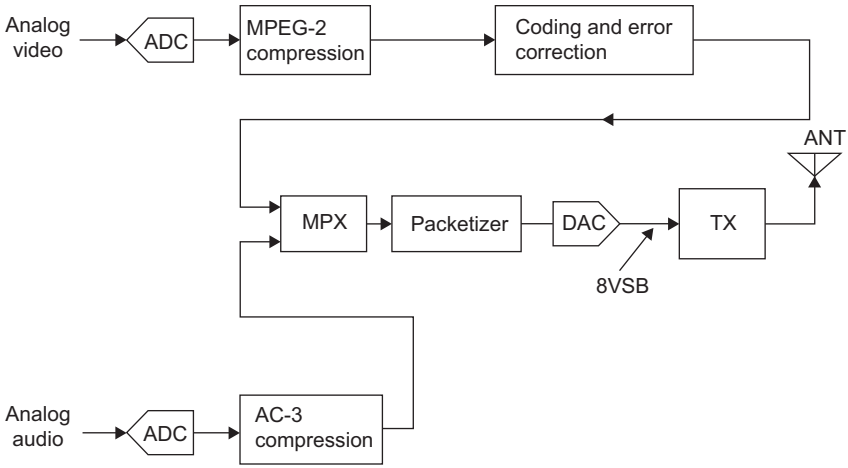


FIGURE 11.9 General block diagram of TV transmitter.

TV Transmission

The compressed audio and video of a TV signal are assembled into packets or frames that look like that in Fig. 11.8. The 4 bytes up front provide synchronizing bits for the receiver. The ID header tells the packet number, sequence, and video format used. The remaining bits are the serial compressed video and audio.

Fig. 11.9 shows a simplified TV transmitter. The serial digital video is put through the MPEG-2 compression process. This is followed by additional bit manipulation and coding for error correction and improved signal recovery by the receiver. This serial data is then multiplexed with the serial compressed audio data. Then the packets are formed. This is what will modulate the transmitter.

The modulation begins by translating the fast serial bitstream into an eight-level signal with a DAC. Each 3-bit segment of the serial data is assigned a specific voltage level as shown in Fig. 11.10. Since each level represents 3 bits, you can transmit more bits per second in the same time period. It is this eight-level signal that modulates the transmitter carrier. The modulation is AM, where all of the upper sidebands are transmitted but only part of the lower sidebands. This saves spectrum. The modulation is referred to as 8VSB for *vestigial sideband*, where vestigial refers to part of the lower sideband. The signal is then upconverted to the final frequency by a mixer. A high-power amplifier in the transmitter sends the signal via coax cable to the antenna. Typical TV station

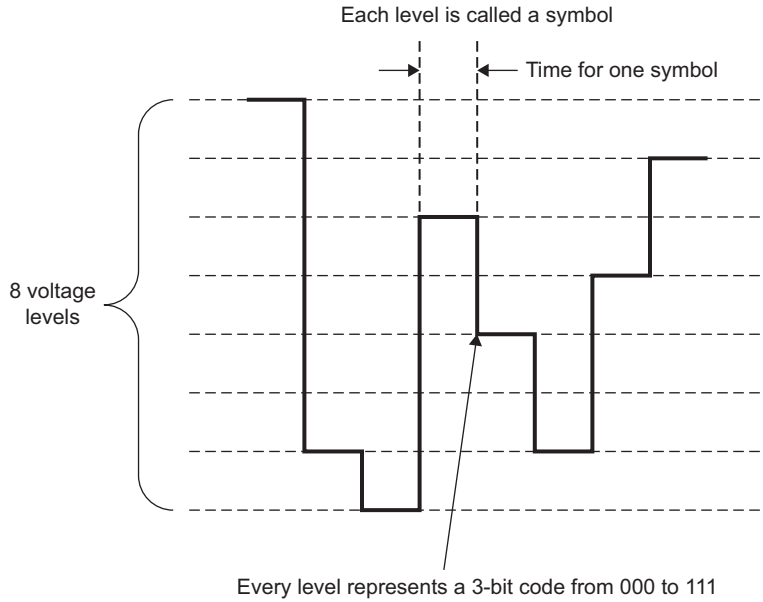


FIGURE 11.10 US ATSC system translates the digital bitstream into an eight-level signal to transmit multiple bits per level, making higher data rates in a given bandwidth possible.

range is about 70 miles maximum, and that is determined by tower height and terrain. The standard for OTA DTV in the United States was developed by the Advanced Television Standards Committee (ATSC). A new standard for 4K UHD TV called ATSC 3.0 using orthogonal frequency division multiplex (OFDM) instead of 8VSB is forthcoming.

In the United States, each TV channel is 6 MHz wide. There are 50 channels starting at channel 2 from 54 to 60 MHz. Channels 3 through 6 range from 60 to 88 MHz. Channels 7 through 13 run from 174 to 216 MHz. Channels 14 through 51 run from 470 MHz and ending with channel 51 from 692 to 698 MHz. In the United States the 600–700 MHz channels are no longer used for TV and are being repurposed for cell phone use and wireless broadband services.

World Digital TV Standards

The US DTV standard from ATSC has also been adopted by Canada, Mexico, South Korea, and a few others. However, the rest of the world uses different digital formats. The UK, Europe, Australia, and New Zealand use a standard called Digital Video Broadcasting (DVB). Another is the Integrated Services Digital Broadcasting (ISDB) standard used in Japan, South America, and some African countries. The Digital Terrestrial Multimedia Broadcasting (DTMB) standard is used in China. What all these non-US standards have in common is the use of OFDM modulation that has proven superior in OTA transmissions. The United States plans to adopt OFDM in its forthcoming ATSC 3.0 standard for 4K.

TV Receiver

Fig. 11.11 shows a general block diagram of a modern DTV receiver. The signal from the antenna or cable TV box is sent to the tuner where the signal is amplified and sent to a mixer along with a local oscillator signal to downconvert the signal to a lower frequency called the *intermediate frequency* (IF). This is commonly 44 MHz. The local oscillator is a frequency synthesizer that selects the desired channel, usually with a remote control. The IF signal is filtered to select only the desired 6-MHz channel.

The IF is then sent to an ADC for digitizing. The 8VSB signal is then recovered in the demodulator. It is then translated into the original bitstream, and any coding or error correction is removed. The signal is then demultiplexed into the video and audio streams. The video goes to an MPEG-2 decompression circuit for recovery of the original video. The individual RGB components are sent to DACs to recover the picture detail. The RGB signals are then amplified and sent to the screen for display. The audio is also decompressed and sent to the DACs and amplifiers and speakers.

The whole TV set looks something like Fig. 11.12. Note all the possible inputs. The set gets its RF inputs from the antenna or cable box. The cable box may also have a digital signal output, meaning the cable box does all the decoding, demultiplexing, and decompression. The output comprises a serial data stream of the video and audio. A special high-speed digital interface called the *high-definition media interface* (HDMI) is used. It uses a special cable no more than 15 ft long and with a special 19-pin connector. The HDMI carries video and audio from the TV to cable box or DVD player or vice versa.

Some TV sets also accept analog video inputs from other sources such as VCRs, video cameras, and digital cameras. A special fiber optic cable input called TOSLINK serves as the interface for TV sets, cable boxes, and DVD players.

Finally, some TV sets include standard computer interfaces such as USB or Ethernet ports. The so-called Smart TV sets are configured for Internet access from a modem by way of the Ethernet port or a built-in Wi-Fi wireless capability.

TV set outputs, of course, are sent to the screen and the speakers. A remote control sends infrared (IR) or RF wireless signals to an embedded controller that tells the set what to do.

TV Screen Technology

As indicated earlier, there are several ways that the video signal is translated back into a viewable picture. The CRT used in older sets is gone. LCD screens are by far the most popular and most widely used today. Plasma screens and DLP projection screens have mostly disappeared. There are other emerging technologies that we may see in the future. In any case, what we need is a light source to reproduce the varying intensities of red, green, and blue light.

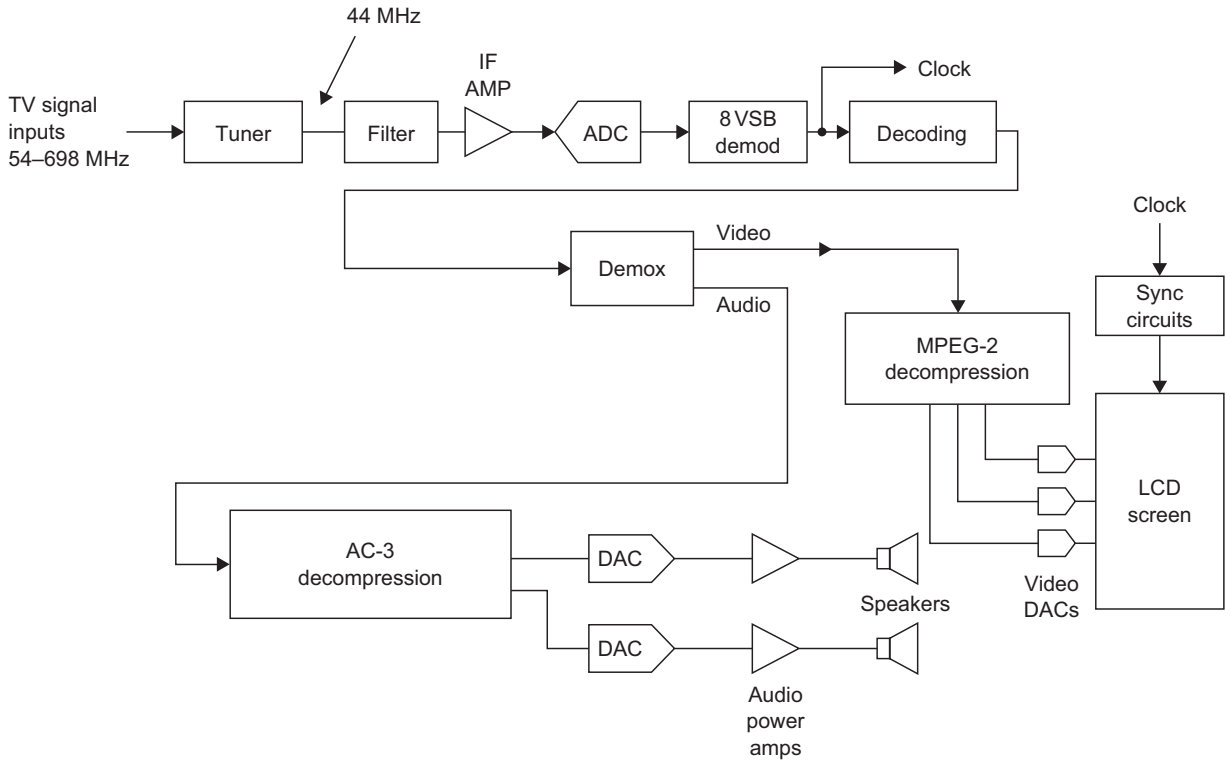


FIGURE 11.11 Simplified block diagram of digital TV set.

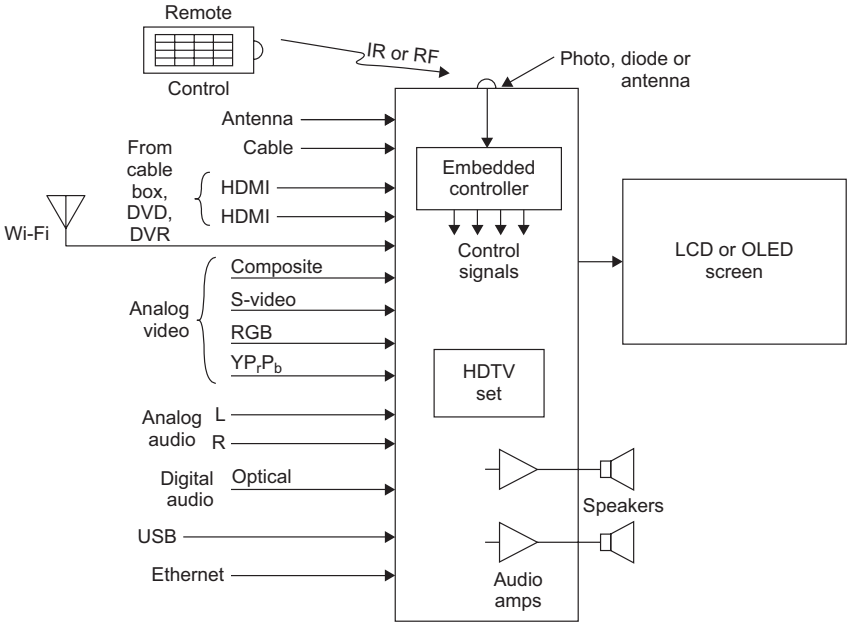


FIGURE 11.12 Inputs and outputs of modern digital TV set.

Color video screens are made up of a very large number of tiny red, green, and blue light sources. These are used to make up the pixels or dots of light that recreate the picture. These pixels are very small, so that your eye cannot actually see them even when you are relatively close to the screen.

Fig. 11.13 shows one example of a screen pixel format in use today. LCD and LED screens use a pixel format somewhat like that shown in Fig. 11.13. These are usually rectangular red, green, and blue areas. They are LEDs that produce their own light or are LCDs backlighted with the appropriate degree of intensity.

One pixel as displayed on the screen might actually be made up of a collection of these three color groups. The actual pixel size may be something like Fig. 11.13, made up of multiple groupings of red, blue, and green elements as shown.

The actual format displayed on the screen is determined by the TV display standards. As indicated earlier, a standard DTV screen uses 480 horizontal lines with 640 pixels per line. That creates a screen with a total of 307,200 pixels. The 720×1280 screen puts 1280 pixels on 720 lines for a total of 921,600 pixels. HD screens use 1080 lines with 1920 pixels per line for a total of 2,073,600 pixels. Just remember that the pixels are turned on one at a time from left to right and top to bottom on the screen at a very high rate of speed.

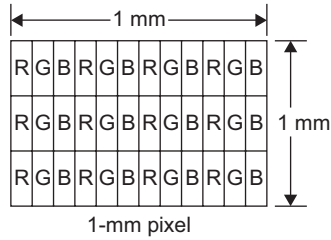


FIGURE 11.13 How color pixels are formed on a TV screen. Pixel format typical of LCD or LED screens.

Summary of Screen Technologies

The actual technical details of each of the different types of screens are way beyond the scope of this book, but a summary might be useful. A quickie review of each of these screen types follows.

CRT—No longer used in modern TV sets.

LCD—Liquid crystals are, as their name implies, a liquid made up of molecules whose physical orientation can be changed by the application of an electric signal. Different voltages change the polarization of the light through the liquid. By applying one level of voltage to the liquid crystal, it can be made almost totally transparent where maximum light passes through it. Another level of voltage will twist the molecules and practically block all light from being passed. In this way, the liquid crystal acts almost like a camera shutter but in this case with varying degrees of transparency being possible. The liquid crystal material is contained within glass plates. A bright light source, such as a fluorescent lamp or high-brightness LEDs, is placed behind the liquid crystal. In front of the liquid crystal is another transparent sheet containing the red, blue, and green pixels described earlier. The whole thing is sandwiched together in a very thin screen. The electrical signals applied to a matrix of wires cause the liquid crystals to be properly oriented for each pixel and to allow the correct proportion of light through to each of the red, blue, and green light filters.

Plasma—Plasma screens are no longer popular.

DLP—DLP TV sets are no longer available.

OLED—The newest TV screens are made of tiny organic red, green, and blue LEDs arranged in a pixel matrix as described earlier. The base is an electroluminescent layer of film made of an organic compound. The organic or OLEDs omit their own light so no backlight is needed. They typically have a wider contrast for an improved picture. A newer enhanced version is called quantum dot technology. QLEDs as they are called give brighter colors. The OLED screens are the brightest available and respond fast to action scenes. However, they are the most expensive screens.

3D TV

Yes, you actually can buy a 3D TV set that gives you that same 3D "coming-at-you" feeling of theater 3D. These sets are very expensive, and there is very little 3D material to see. Right now it is only available on DVD. And, yes, you still have to wear the special glasses. These glasses are not the red and green lens type but a special electronic version. The lenses use electrical polarization like a shutter that turns the left and right lenses off and on in synchronization with the two alternating sets of frames on the screen. A wireless signal (IR or radio) signals the glasses when to switch. The switching occurs at very high speed so the effect is to see the 3D scene. 3D TV has not been widely accepted and for now will remain a gimmick or niche TV product.

Which Screen Type Is Best?

LCD screens are available in a wide range of sizes, but the minimum today for a TV set is about 19 in. Remember that these dimensions are the diagonal dimension from an upper corner of the screen to the lower diagonal corner. A popular LCD screen size is 32 in., but they are available in a wide range of sizes such as 42, 55, 65, 85, and 105 in.

The ability of a screen to produce high-speed motion is generally good on LCD screens. However, some early LCDs did produce some smearing. Recently the higher scan rates of 120 and 240 frames per second have essentially eliminated this problem.

LCD screens dominate TV today as their price continues to drop with better manufacturing methods. LED and organic LED (OLED) screens are growing in popularity and will become more widely used as prices come down in the future. Even curved screens are now available but expensive and not popular as they offer no improvement in picture quality and suffer from a narrower angle of view.

CABLE TELEVISION

It is estimated that about 15% of all US citizens get their TV over the air with an antenna. But over 80% get TV via some pay TV service. Roughly 60% get TV from cable. While the remaining 20% get satellite TV. Why? Mainly because generally cable offers not only better, more reliable signals than by antenna, but also offers hundreds of channels of programming. But that is not all. Most of those who have cable also use the cable connection for high-speed Internet access service. Of course, you pay for all that, and it has become like a monthly utility bill. With the cable industry being so big, it pays to know a little more about it.

It all starts with a facility called the *cable head end*. Another name you might hear is cable modem termination system, which specifically is the

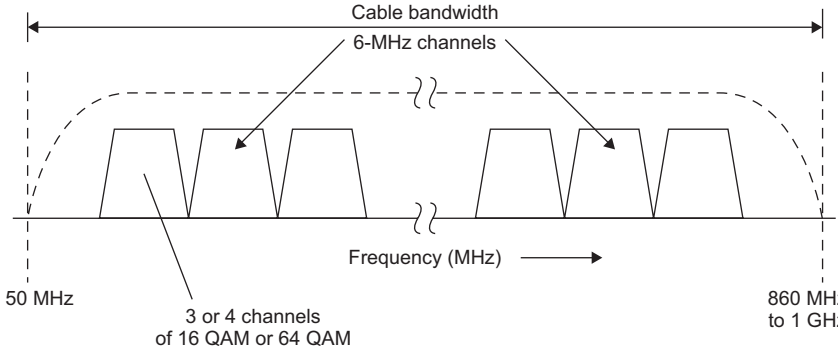


FIGURE 11.14 Coax cable bandwidth up to 1 GHz can contain about 130 6-MHz channels.

equipment at the head end. This is a place where the company collects video and programming from many different sources. It snatches signals off the air, it receives premium programming such as HBO, ESPN, Showtime, and Fox via satellites, stores movies on its large computers called video servers, and may even do some of its own local programming. The result is a hundred channels or more.

Now each of those TV signals—video plus audio—is modulated onto carriers that are spaced 6 MHz apart just like the regular OTA TV channels. Then all of those modulated carriers are added together to form a very complex signal. That signal is then amplified and put on the outgoing cable. Fig. 11.14 shows what the spectrum looks like. Most cables have a bandwidth from about 50 MHz up to about 860 MHz–1 GHz, which will accommodate up to about 130 6-MHz channels. We call this process frequency-division multiplexing, where a single cable can carry many separate channels of data, each on a different frequency and bandwidth. And since the cable is shielded, it does not radiate, so it, in effect, duplicates the free-space electromagnetic spectrum.

Since TV today is digital, digital modulation methods are used to put multiple TV signals within each 6-MHz channel. Using 16-QAM or 64-QAM, a cable company can squeeze several channels of video/audio into each 6-MHz chunk of spectrum, providing hundreds of additional slots for programming. That is why cable companies can advertise up to 500 channels of entertainment, news, and so on.

All of the digital video/audio signals are then remodulated onto different channel assignments. All of these 6-MHz channels are added together or linearly mixed in a multiplexer (MUX) to create a massively complex composite signal. This is what goes out on the cable (see Fig. 11.15).

The signal distribution network is called a *hybrid fiber cable* system. This multiplexed signal is applied to a fiber optic cable, called a *trunk cable*. It is routed around the city, and it terminates at selected points where the signal is divided into multiple paths of coax cable. These so-called *feeder cables* are

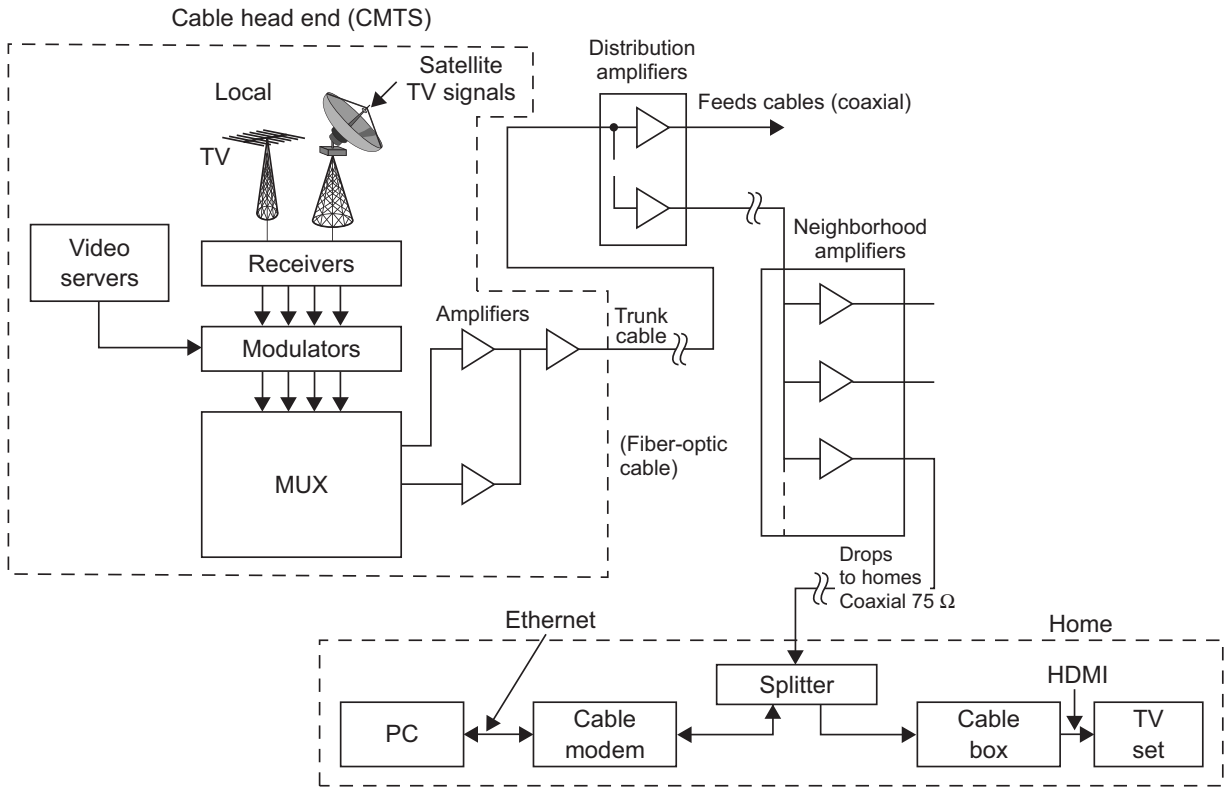


FIGURE 11.15 General block diagram of modern cable TV system.

connected to amplifiers along the way to overcome the large attenuation of the cables. At some point, the feeder cables come into your neighborhood and are further amplified and split into multiple signals. These signals are then sent to your house by a coax drop cable. The most common type is 75-Ω RG-6/U coax with F connectors. The cable comes into your home and is usually split two or more times and sent to wall connectors in the various rooms. These connectors connect the signal to a cable box and/or a cable modem for Internet access to a PC or a Wi-Fi router.

The cable box is like a tuner in that its main job is to select one of the many channels and send it to your TV set. Fig. 11.16 shows a simplified block diagram of a typical cable box, usually called a set-top box (STB). The input is a TV tuner with channel selection via a frequency synthesizer local oscillator by way of your remote control. New STBs feature two or more tuners so that you can watch one channel and record another. The selected signal is then demodulated and decompressed by a digital media processor chip and then sent to the TV set via one of the many possible interfaces, usually the HDMI or *high-definition multimedia interface*. This is a very fast digital interface with special cable and connector. Most TV sets have this as the most common input. Other video format interfaces, such as RGB, PrPbPy, or S-video, are usually provided to accommodate older analog TV accessories. An additional feature of many of the newer STBs is a built-in digital video recorder (DVR). This is essentially a computer hard disc drive that records the program you want to save for viewing later.

Other Wired TV Distribution Systems

There are a couple of other ways that digital video is distributed to homes. One is a fully fiber optic system. The fiber cables go all the way from the head end to the homes. This was once too expensive, but today, thanks to improved fiber and other technologies, it is cost effective. Such systems are generally referred to as *passive optical networks* (PONs). "Passive" simply means that the signals are strong enough and the cable runs short enough so that no amplification is needed along the way. The digital video and audio are modulated onto IR light beams and sent down the cable. Because fiber has such wide bandwidth, data rates are extremely high, over 1 GB/s in the newer systems. This allows not only digital video to be transmitted but also very-high-speed Internet service. Such systems use standards such as Ethernet PON or GPON for gigabit PON. Typical US systems are Google Fiber and Verizon Fios.

TV is also distributed over digital subscriber lines (DSLs) (Chapter 9). The signals travel via fiber to the neighborhoods. From there they are split off, and the signals travel via in-place twisted-pair telephone lines. New forms of modems using a form of OFDM called *discrete multitone* transmit the signal over the twisted pair at high speeds. These lines are now used just for high-speed Internet service and are referred to as *asynchronous digital subscriber lines* (ADSLs or just DSLs). Newer versions called ADSL2 and ADSL2+ or VDSL for video DSL provide data rates from 26 to 52 Mbps on standard phone lines. Newer systems use an advanced form of DSL called G-fast that can achieve an aggregate of 1 Gbps on standard installed lines.

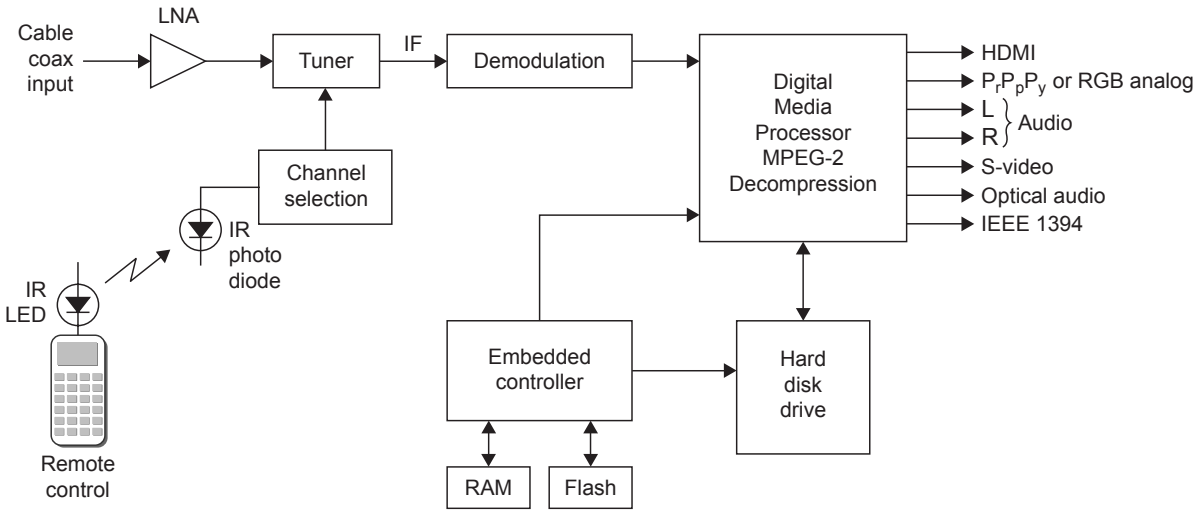


FIGURE 11.16 Simplified block diagram of modern cable box with DVR.

For Internet access, you connect a cable modem to the coax cable, and it automatically selects the channel where the data services are assigned. The modem goes to your computer or a Wi-Fi router via an Ethernet cable.

SATELLITE TV

Satellite TV technically is also OTA TV or radio, but instead of the signals coming from one or more local TV stations over broadcast towers, the signals emanate from a geosynchronous satellite 22,300 miles away orbiting around the equator (see Fig. 11.17). The satellite transponders operate in the Ku band with frequencies of 10.95–14.5 GHz. This system is referred to as *direct broadcast satellite*.

The satellite TV company gets its TV like the cable companies and brings it all together at a single Earth station head end where it is all collected and transmitted on an uplink to the satellite in the 14–14.5 GHz range (see Fig. 11.18). The signals are then amplified in the satellite and rebroadcast on the downlink frequencies at 10.95–12.75 GHz. A high-gain antenna focuses the signals on the United States or other country of interest.

Down on Earth, satellite TV subscribers have a special receiver and antenna. These are illustrated in Fig. 11.19. The antenna is usually a small dish or parabolic reflector antenna about 18 in. in diameter. The antenna is usually a small horn. Also inside the antenna assembly is a low-noise amplifier (LNA) to boost the small signal from the satellite. This is then sent to a mixer along with a local oscillator signal to downconvert the signals into the 950–2100 MHz range. This signal is then routed by coax to the satellite receiver. The LNA/mixer assembly at the antenna is called a low-noise block converter. This receiver signal processing at the antenna is necessary because the Ku band frequencies of 10.95–12.75 GHz are so high they would be far too greatly attenuated by the antenna

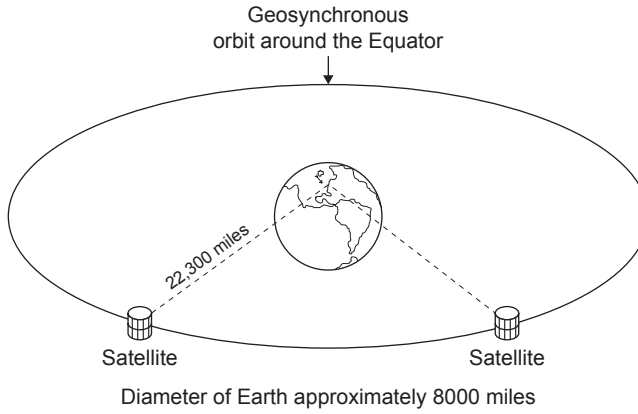


FIGURE 11.17 TV distribution satellites in geosynchronous orbits act as wireless relay stations.

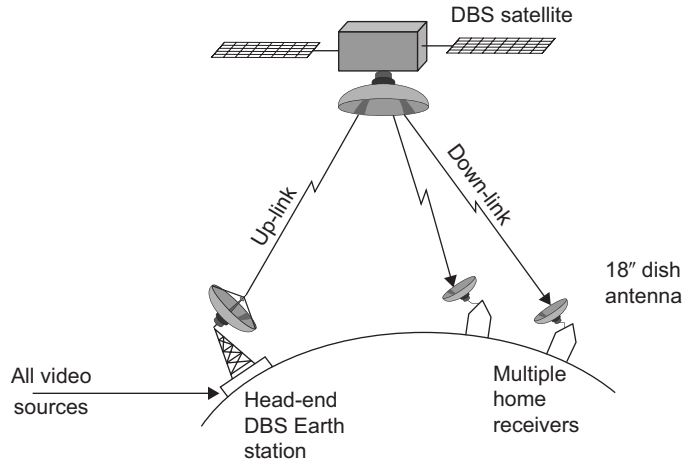


FIGURE 11.18 Video from all sources is transmitted uplink to satellite that rebroadcasts it back to Earth over downlink to home receivers.

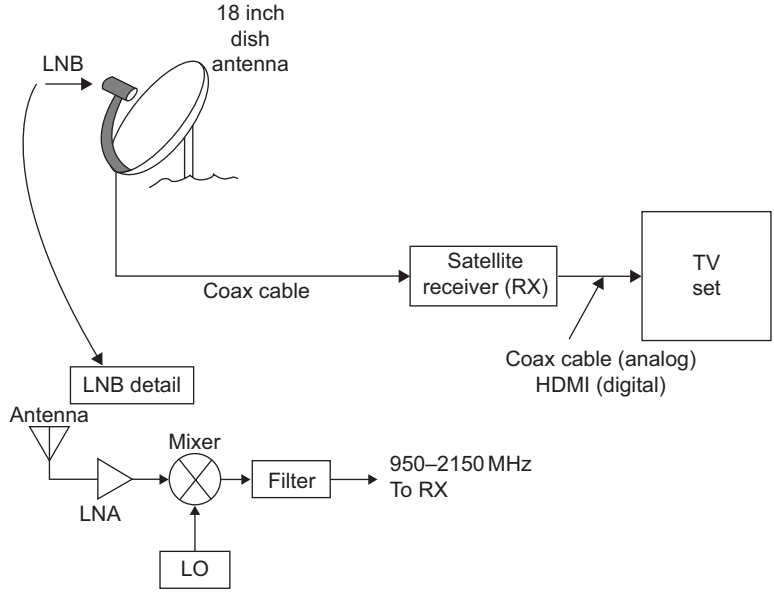


FIGURE 11.19 Satellite TV home system consists of antenna with low-noise block converter, receiver, and TV set.

coax cable to the receiver. So downconverting to the lower frequency allows coax to be used to the receiver.

The satellite receiver is like the cable box in that it is used to select the desired channel and demodulate it for the TV set. The satellite signals are all digital and transmitted in packets 147 bytes long. A satellite receiver is shown

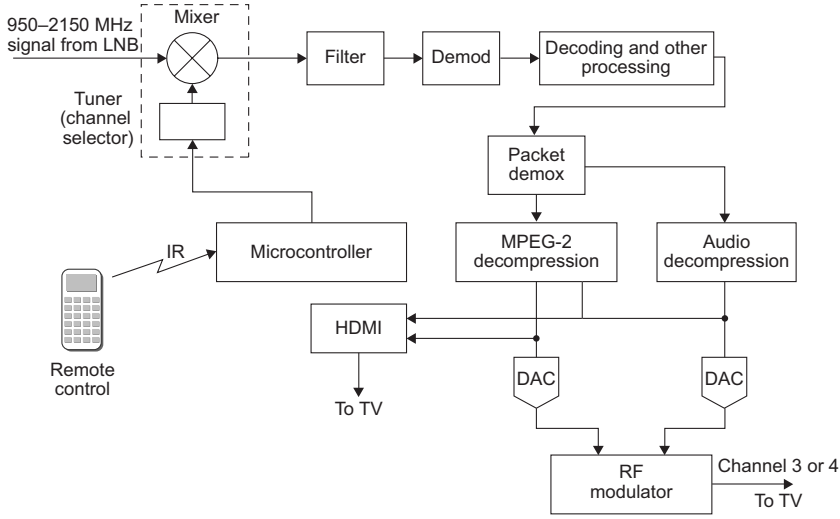


FIGURE 11.20 Simplified block diagram of satellite TV receiver.

in Fig. 11.20. MPEG-2 video decompression is used. The recovered signals are then sent to a DTV receiver, typically via an HDMI port.

OVER-THE-TOP TV

Over-the-top (OTT) TV is a video that streams the DTV signal to you over the Internet. In the United States some of the popular sources are Amazon, Hulu, and Netflix. The signal comes to you by your cable or DSL service usually to a Wi-Fi router. The router delivers the signal wirelessly to an OTT box or converter. Some common boxes are from Apple TV, Roku, or Amazon. The box is then connected to your TV set by and HDMI cable. Smart TVs have the Wi-Fi built in.

Streaming means that the compressed video comes to you in real time assuming your Internet service is fast enough. Streaming is video as it is occurring in contrast to downloading a video and storing it for play later. Your OTT box usually buffers or stores the video stream and feeds it continuously to the display.

Movies are the most common content but also available are older TV series, documentaries, and travel videos. Audio can also be streamed this way from services such as Spotify.

CELL PHONE TV

You can watch TV on your smartphone and you probably already do. Short video clips come via text or email. With Internet access you can also see TV from a mix of sources such as YouTube. If you have an OTT service such as

Amazon, Hulu, or Netflix, you can watch TV series and movies by way of a Wi-Fi connection to your home router and OTT provider box (Roku, Apple TV, etc.) The picture is small but of high quality.

CLOSED-CIRCUIT TV

Closed-circuit TV (CCTV) is used primarily for surveillance. You have seen the small wall- or ceiling-mounted TV cameras in stores, airports, companies, and today on the streets. The video signals are routed to a central point where multiple TV sets or monitors are set up for observation.

In many installations, the video is transmitted directly over coax cable to the monitors. There is no modulation involved. However, in some cases, when remote cameras are used, a wireless link via 2.4 GHz is typical. Of course, modulation is then used in the transmission so that a receiver is needed at the viewing end to recover the video.

Many installations also have video recorders (VHS tape or DVD) to capture several minutes or hours of video. In the past, most cameras were black and white, but today more and more use color and high definition.

DIGITAL VIDEO DISCS

The formal meaning of DVD is *digital versatile disc*. Its main use is video but it can also store computer data or audio. It is the storage medium of choice for movies, music videos, and other video programming. It has virtually replaced the VCR.

The basic DVD storage medium is a disc that is almost identical to the CD discussed in Chapter 10. The disc is the same size (120-mm diameter), but it is formatted differently to store many more bits and bytes of data. While the CD can store up to about 700 MB, the DVD can store about 4.7 GB, that is, gigabytes or billions of bytes. And that is just the basic one-sided disc. There are also single-side/double-layer discs, double-sided/single-layer, and double-sided/double-layer versions that can store even more, up to 15.9 GB.

The storage method is the same. A laser beam burns pits into a spiral track. The data is represented as pits and lands as described earlier in the CD discussion (see Figure 10.6). The big difference is that the size of the pits is significantly smaller and the track spacing is less than half the CD spacing, that is, 1.6 µm (1600 nm) versus 740 nm. A nanometer is 1-billionth of a meter. With smaller pits and tighter spacing, the disc can hold significantly more data.

But that is not the whole story. The video is also compressed. Unlike the audio on a CD, which is not compressed, digital video is compressed with the MPEG-2 standard described earlier. This gives roughly a 40-to-1 compression. In that way, a full 2 h of video can be stored.

As for audio, the format is as described in Chapter 10 for CDs, but DVD audio is Digital Dolby Surround Sound 5.1 using six channels of 16-bit,

44.1-kHz digital sound. Audio DVDs are also available with 192-kHz sampling of the audio with 24-bit ADCs, giving even greater fidelity and low-noise performance.

How a DVD Player Works

Fig. 11.21 depicts the block diagram of a typical DVD player. First, note the motor that drives the disc. It is a variable-speed device that changes speeds as the pickup mechanism moves from inside to outside as it reads the spiral track. The pickup head uses a laser that shines on the disc to read the pits and lands. Because of the closer spacing, a higher-frequency (shorter wavelength) laser is used. CD players use a 780-nm laser, while DVD players use a 640-nm laser that has a smaller focused beam.

The photodetector in the head picks up the laser reflections and sends the 10 Mb/s data stream to the processing chips. In some players, a single-chip application-specific device handles all of the digital processing from demultiplexing, to error detection and correction, decoding, and MPEG-2 decompression. All this may be in separate chips in some players.

In any case, the MPEG-2 data goes to a video decoder and to multiple DACs that recreate the original analog RGB signals. Various video formats are used, such as RGB, YCrCb, and YPrPb, each of which needs three DACs each. Most DVD players also decode regular composite video and S-video.

The separated audio signals go to an audio codec that contains the DACs that recover the audio content either in basic stereo or 5.1 surround sound. As

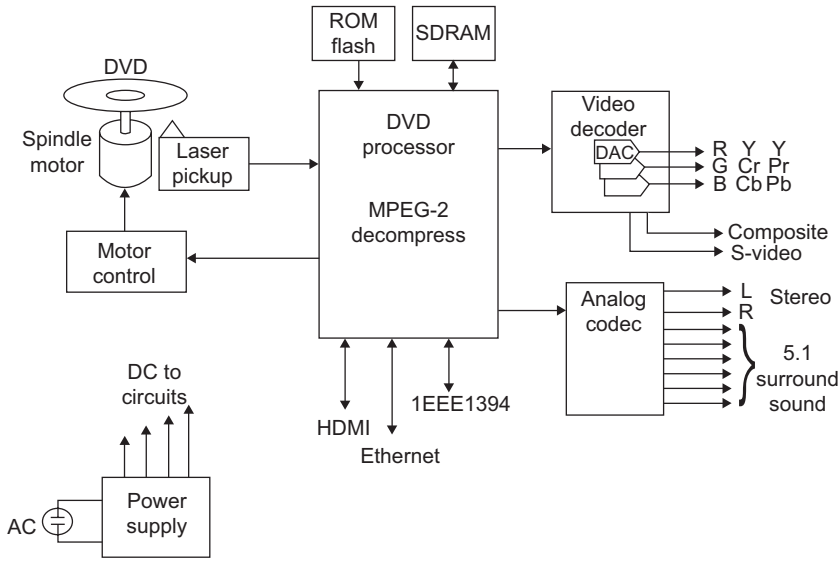


FIGURE 11.21 Block diagram of standard DVD player.

for interfaces, an HDMI output is provided. Most players also have an Ethernet port and USB connections.

Do not forget that some of the later models are also DVD recorders. They play DVDs but also burn new ones with video from the TV set, cable box, satellite box, or a built-in tuner.

Blu-ray DVD

Blu-ray is the most recent generation of DVD medium and players. The discs are the same size but thanks to even smaller pits, lands, and track spacing, even greater storage capacity is available. With 320-nm track spacing and a 405-nm (blue light wavelength) laser, the single-sided disc can hold up to 25 GB of data. That is enough to store two full-length HD movies or 13 h of standard-definition video. A double-layer version is also available that doubles those storage figures. Blu-ray uses MPEG-2 compression but also supports other video compression standards such as MPEG-4/H.264 and VC-1.

Virtual and Augmented Reality

Virtual reality (VR) is an emerging video specialty that is used to reproduce or simulate an alternative reality. Using computer generated images and related sound, the user can experience an almost real or even an imaginary environment. 3D images can be produced.

VR is experienced by way of special goggles called a VR headset. This binocular head-mounted display completely covers the eyes and is often used with speakers or headphones in addition to motion sensors attached to the hands to duplicate motion and generate interaction and other involvement in the scenes presented. The computer generated scenes and situations that make the viewer feel as though they actually exist in this artificial setting. Various scenarios are produced, presented, and interacted with by the user.

Commercial VR products are now available from several sources. A powerful PC is required to meet the software requirements. Most of the software is related to computer games although a developing application is simulating real environments for training and education. Other applications are being explored.

VR produces a very real, immersive, and sometime intense experience. Any simulated motion has produced nausea in some users.

Augmented reality (AR) is a variation of VR that also uses goggles to enhance an existing scene or environment. The user views a current setting directly or by way of a video camera and that scene is overlaid with a computer-generated augmentation for some application. A heads-up display in a car windshield is a type of example. A current scene or situation is artificially modified by the computer overlay in real time.

AR applications are still developing, but current uses include games, military, training and education, manufacturing, and medical. Microsoft HoloLens is an AR product.

Project 11.1

Look at a Pixel

Get a magnifying glass and hold it up to your TV screen to see the individual color pixels or subpixels. What is their shape?

Project 11.2

Try Over-the-Air TV

If you get your TV by cable or satellite, try receiving local channels on an antenna. Use an indoor antenna for simplicity. You can buy a set of "rabbit ears" or other indoor antenna from a local electronic store such as Best Buy, Fry's, or Walmart. Or try an outdoor antenna. You can get some channels on a simple loop of wire 1 yard long.

This page intentionally left blank

Chapter 12

Industrial Control

How to Automate: Monitor, Process, and Control

In this Chapter:

- Control defined.
- Open and closed control systems.
- Sensors and transducers.
- Actuators like relays, solenoids, and motors.
- Thyristors.
- Programmable logic controllers.
- Data acquisition systems.

INTRODUCTION

Industrial control is one of the four major applications of electronics. In industrial control, electronic components, circuits, and equipment are used to operate various types of machines in manufacturing plants. Most industrial machines such as robots are mechanical in nature but electrically operated. Most are powered by electric motors or other actuators. To operate the machine, electrical power must be properly controlled. Industrial control electronics is used to turn machines off and on at the appropriate time, control their speed of operation, and otherwise produce the desired manipulations.

Electronic control is not confined to industry. There are lots going on in the home and car as well. The principles given here apply to those applications as well.

OPEN- AND CLOSED-LOOP CONTROL

The basic industrial control process is illustrated in Fig. 12.1. Electrical inputs, such as switches, sensors, or other devices, are used to initiate an electronic control process. The signal-processing circuits generate control output signals that are used to operate the industrial machines. This basic process is known as open-loop control. The typical device being controlled by the output signals is an electric motor that operates a machine. Other outputs could operate lights, relays, solenoids, or a variety of other devices.

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00012-6
Copyright © 2018 Elsevier Inc. All rights reserved.

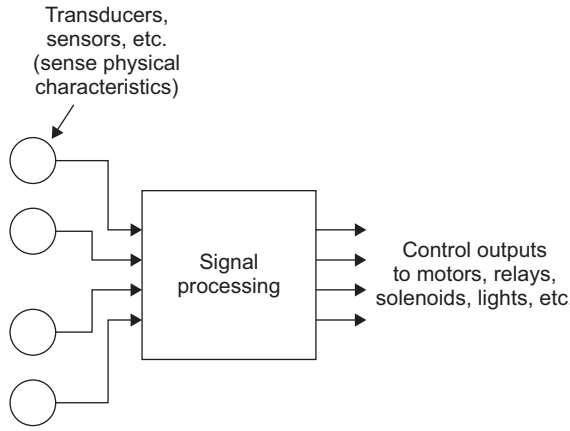


FIGURE 12.1 General block diagram of industrial control process.

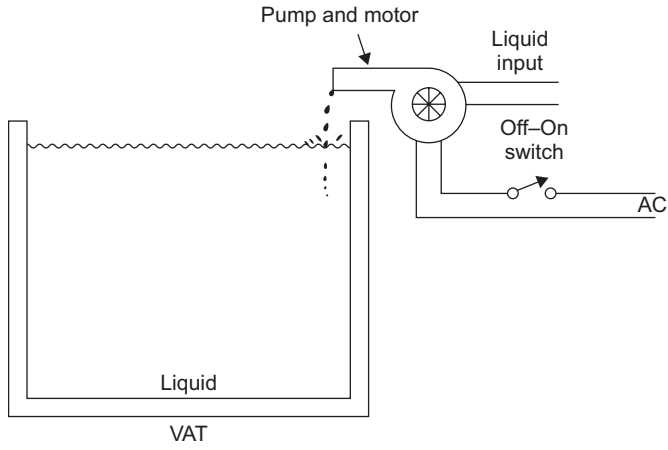


FIGURE 12.2 Open-loop control system for filling vat with liquid via a pump.

Open-Loop Control

A simple example of an open-loop control system is shown in Fig. 12.2. The input is a switch that applies electrical power to a motor. The motor, in turn, operates a pump that causes liquid to be put into a vat or tank. As soon as the vat is full, the operator turns the switch off. The basic control process in this system is simply turning power off and on to control the pump. The operator visually monitors the level in the vat until the correct level is reached.

Closed-Loop Control

An improved form of industrial control system is illustrated in Fig. 12.3. It is known as a closed-loop control system. The system is given an initial input

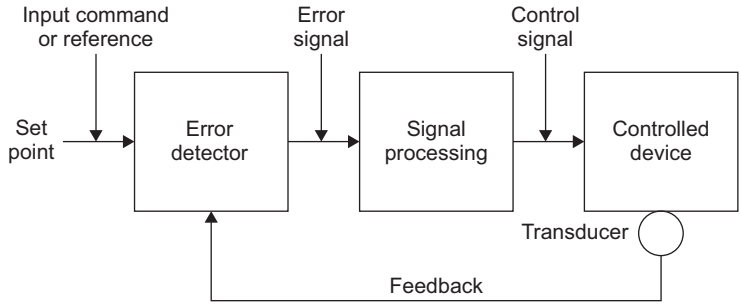


FIGURE 12.3 Generic diagram of any closed-loop control system with feedback.

reference called the set point. The set point is usually a voltage that represents some physical value that is to be achieved. It is applied to an error detector that compares this input to a signal from the controlled devices. If the two signals are different, an error output is produced. This error signal is processed (usually amplified), and an output control signal is derived from it. It is this output signal that operates the controlled device. A transducer monitors the controlled device to see that the desired outcome is obtained. The signal from this transducer is called *feedback*. The feedback signal is compared to the input to produce the error signal. The control signal operates the controlled device until the error is reduced to zero. At that time, the desired output condition, where the feedback equals the set point, is obtained.

The key to closed-loop control is the feedback. Feedback signals tell the system whether the machine is performing correctly. The feedback signal allows the system to adjust itself in such a way that the desired output is continuously accomplished. Control is automatic.

A closed-loop version of our system to fill a vat with liquid is shown in Fig. 12.4. An initial input signal is applied to start the process. If the vat is not full, the transducer will sense it and send a signal to the error detector that says the liquid level is low. The error detector generates an output signal that is processed and used to start the pump motor. The motor rotates the pump, which puts liquid in the tank. When the vat is full, the sensor will generate a signal that is sent to the error detector. The error is now zero, so the pump motor is turned off.

The primary benefit of a closed-loop control system is that its operation is automatic. In the open-loop system, an operator has to turn the system off and on manually to fill the tank. In the closed-loop control system, the operator gives an initial input, called the set point, to which the error detector will compare the feedback signal from the sensor. He or she turns the system on. From that point on, operation is automatic. The pump turns itself off when the vat is full. If the liquid level drops below the desired level due to usage, the sensor indicates a low level and automatically turns on the motor so that the pump will again fill the tank. When the tank is full, the unit shuts off by itself.

Most industrial control systems are closed loop to make them automatic. And your home has some as well. Your toilet flusher is a closed loop as is your heating

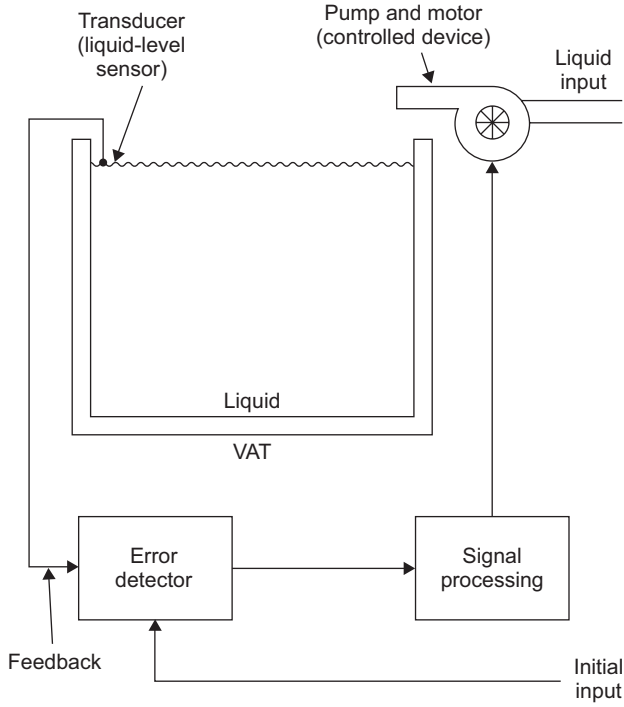


FIGURE 12.4 Filling vat with liquid automatically with closed-loop control system.

and air conditioning (HVAC) thermostat. Appliances such as your washer, dryer, and dishwasher are other examples of closed-loop control. All of them contain a microcontroller with sensors, timers, and feedback to make them totally automatic.

Controllers

While many industrial control applications are implemented with simple control circuits, most industrial control is carried out by specialized instruments called controllers. These units accept inputs from sensors, condition them, process them, and then generate output control signals.

A good example of an analog controller is one used to control the temperature in a system. A resistive temperature sensor is used to monitor the temperature of the liquid in a pipe. If the temperature goes up, the sensor output goes up. This is sensed by the controller circuitry. Inside the controller, a comparator is set to a desired temperature threshold. Should the temperature exceed a specified set point, the controller will turn off the device heating the pipe and liquid. Should the temperature drop below another set point temperature, the controller will turn on the heating device in an effort to maintain the set point temperature. While the heating element will be turning off and on, it will produce the desired average overall temperature.

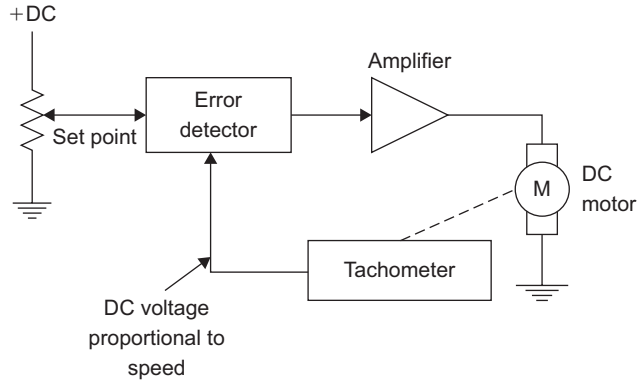


FIGURE 12.5 Closed-loop control system for motor speed control and regulation.

A continuous analog controller will provide proportional control rather than an on/off response. For instance, suppose that you want to control the speed of a motor. The system depicted in Fig. 12.5 does this. You want the motor to stay set to the speed you want, say 1200 rpm. A pot connected to a voltage represents that speed value. The voltage is applied to an error detector along with the feedback input from a tachometer. A tachometer is a device that senses rotational speed and develops a proportional DC voltage. That voltage is sent to the error detector and compared to the set point. If they are different, an error voltage is developed. This voltage is then amplified and applied to the motor. The speed of a DC motor is proportional to the voltage applied to it. So if the motor slows down, the error voltage is increased and that is amplified and applied to the motor speeding it up to compensate for the speed drop. A speed up in the motor produces an increased tachometer output. The resulting error signal causes the motor speed to drop until the error is zero. With such a circuit, the motor speed remains constant.

An analog controller is a product made up of the set point pot, error detector, and a selection of amplifiers whose gain can be varied and an output amplifier that can drive the motor or other device. Many different types of commercial electronic controllers have been developed to monitor and control physical characteristics such as pressure, physical strain, weight, liquid flow rate, physical position, or liquid level in a tank. Digital controllers that contain a microcomputer are also available.

SENSORS

An essential element of most control systems is the inputs from sensors. Sensors are the components that detect physical changes or events and convert them into electrical signals to be processed. Sometimes the term transducer is used to refer to the sensor. A transducer is a device that converts one type of energy into another such as mechanical energy to electrical. There are literally hundreds of different types of sensors. A few examples of the most common types follow.

Temperature Sensors

Temperature is probably the most often sensed physical characteristic. Temperature sensors convert temperature to a resistance change or voltage change. The most commonly used temperature sensors are RTDs, thermistors, and thermocouples.

RTD—An RTD is a resistive temperature device. It is essentially just a platinum wire whose resistance varies with temperature. Most of them have a resistance of 100 Ω at zero degrees Celsius (0°C). As the temperature changes, the resistance changes to reflect the change. RTDs have what we call a linear positive temperature coefficient. That is, as the temperature goes up, the resistance goes up and vice versa.

To convert the resistance variation into a voltage, the RTD is usually put into a bridge circuit as shown in Fig. 12.6. The bridge is initially balanced with the variable calibrate control (CAL) to produce zero output at a given temperature. Then if the temperature varies, the bridge becomes unbalanced and a voltage is produced. This is then amplified into a larger voltage that is a measure of the temperature. The output can be measured with a meter or it can be digitized for use as input to a digital system for display or control.

Thermistor—A thermistor is a resistor whose resistance has a negative temperature coefficient. As temperature goes up, the resistance goes down and vice versa (see Fig. 12.7A). The resistance change is much greater than that of an RTD. The thermistor can be used in a simple voltage divider to develop an output voltage or in a bridge circuit like the RTD (see Fig. 12.7B).

Thermocouple—A thermocouple is a unique type of temperature sensor, as it develops a voltage rather than a resistance change. It is formed with two dissimilar metals. If the junction of the metals is heated, a voltage is developed. The voltage is usually in the millivolt range so that it usually has to be amplified before it becomes useful. The thermocouple's main advantage is its accuracy at very high temperatures.

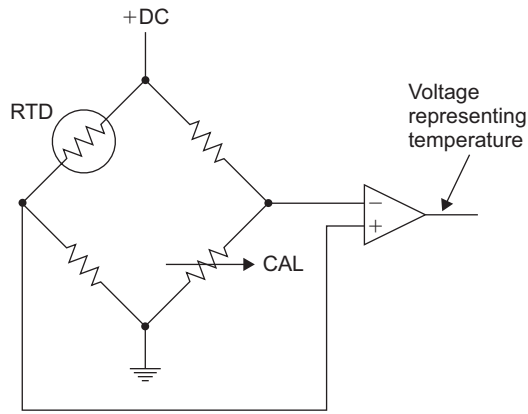


FIGURE 12.6 Most resistive sensors such as an RTD or thermistor are placed in a bridge circuit to condition them to provide amplified output voltage.

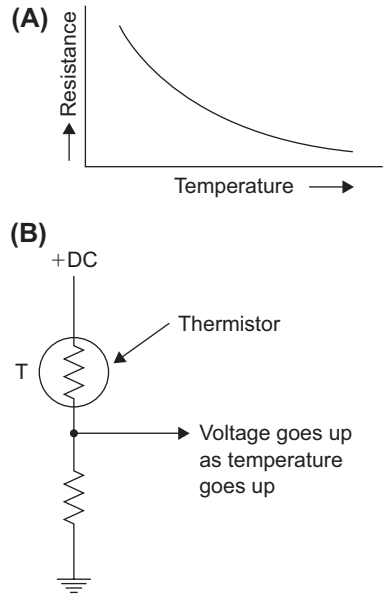


FIGURE 12.7 Characteristic curve of thermistor and simple voltage divider circuit producing output voltage.

Solid state—Diodes and transistors make good temperature sensors. A silicon diode has a very linear voltage drop variation that decreases with an increase in temperature. This is true of the emitter–base junction of a bipolar transistor as well. Zener regulator diodes exhibit a similar response. The sensor is usually packaged into a complete integrated circuit with an amplifier that produces a voltage output proportional to the temperature variation.

Pressure Sensors

A pressure sensor responds to force or pressure. There are many different types. A widely used kind is called a *strain gauge*. A strain gauge is essentially a thin pattern of metal deposited on a plastic base like that shown in Fig. 12.8. It has a specific value of resistance. A value of 120 Ω is common. The strain gauge is then glued or cemented with an adhesive to the object to which the pressure is to be applied. An example is a steel beam. When pressure is applied to the beam, it will bend. As it bends, it stretches or compresses the strain gauge resistance element. If the resistive element is stretched, its resistance increases. If it is compressed, the resistance decreases. Knowing the specific characteristics of the resistance change per pound of pressure, an exact measure of the pressure can be determined. Mostly strain gauges are used in a bridge circuit like that shown in Fig. 12.6. Since the resistance variation is small and the resulting bridge circuit output is small, a special amplifier called an *instrumentation amplifier* is used. It has differential inputs and very high gain.

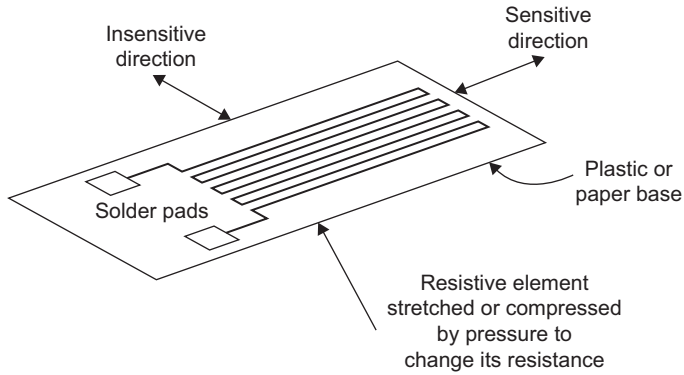

Insensitive direction
Sensitive direction
Plastic or paper base
Solder pads
Resistive element stretched or compressed by pressure to change its resistance

FIGURE 12.8 Strain gauge is a resistive element whose value changes with stress or pressure.

A special pressure sensor called a *load cell* is typically made up of strain gauges. It is fully calibrated to provide a specific voltage output with a specific pressure. Load cells are widely used for weight measurement. An example application is the use of load cells in truck weighing scales.

There are other forms of pressure transducers. Many are solid-state devices with an output voltage proportional to pressure. *Piezoelectric pressure transducers* use the voltage produced by certain types of crystals or ceramics when pressure is applied to them.

Switches

Switches are widely used as sensors. Switches are mechanical devices with electrical contacts that open or close with a particular physical movement. Switches are used to detect mechanical movement and specifically to determine when the limit of some physical device has been reached. Called *limit switches*, these devices have various arms and mechanisms that permit ease of use in a variety of situations. Examples of such switches are those that can detect when a cabinet door is open or closed or a switch that senses when a mechanical device reaches a specific point where motion must be stopped. And of course, a human-operated switch may be the most common. It is usually a button that is pushed to initiate or stop some action.

Potentiometers

A potentiometer is a variable resistor or variable voltage divider. While most electronic pots are rotary devices, they also come in a linear variety. The variable arm of the pot is controlled by some external mechanical device. Then by using the resistance value of the pot or the voltage it produces as a variable voltage divider, it can be used to sense mechanical position.

Photoelectric Sensors

One of the most widely used industrial transducers is a photoelectric sensor. A photoelectric sensor is a component that responds to light and produces an electrical signal that can initiate some operation.

There are three basic types of photoelectric sensors. These are the *photoresistive* or *photoconductive cell*, the *photovoltaic cell*, and the *phototransistor*. The photoconductive sensor is a light-sensitive resistor. Its schematic symbol is shown in Fig. 12.9A. The resistance of the device varies with the amount of light falling on it. With no light falling on the sensor, its resistance will be very high, 100,000 Ω or more. When bright light shines on the sensor, however, its resistance will drop to a very low value, usually several hundred ohms or less. Of course, at a light level between bright and dark, the resistance of the device will be somewhere between 100 Ω and several hundred thousand ohms. The resistance is inversely proportional to the light level.

Another type of photoelectric device is the photovoltaic cell, whose schematic symbol is illustrated in Fig. 12.9B. This is the solar cell described in an earlier chapter. Whenever bright light falls on the cell, it will generate a small DC voltage. The maximum output of a typical photovoltaic cell is approximately 0.45–0.5 V. At lower light levels, the output voltage will be less. Photovoltaic cells are used primarily in power generation systems for producing charging voltage for batteries in satellites and other remote systems. Multiple cells are connected in various series and parallel combinations to get the desired voltage level and current capacity. In some applications, the photovoltaic cell can be used for industrial control. These are also found in portable calculators. Two AA cells at 1.5 V each produce 3 V in series. To generate 3 V with 0.5-V solar cells, you would need to connect six in series ($6 \times 0.5 = 3$ V).

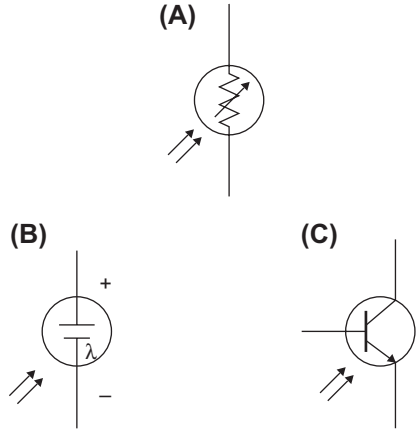


FIGURE 12.9 Schematic symbols for photo cells. (A) Photoconductive or photoresistive, (B) photovoltaic or solar cell, and (C) photo transistor.

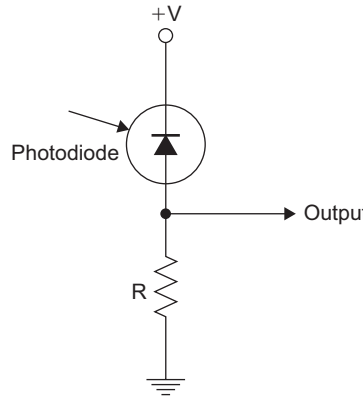


FIGURE 12.10 Photodiode and its simple output circuit.

A silicon diode can also be used as a light detector. Special diodes in clear housings are often used to detect light. These are called photodiodes. Photodiodes are operated in the reverse-biased direction, as shown in Fig. 12.10. With no light falling on the diode, it is cut off, so there is no voltage across R_1. When light strikes the diode, its reverse leakage current increases dramatically, causing a voltage drop to occur across R_1.

A phototransistor is a light-sensitive transistor. Its symbol is given in Fig. 12.9C. It only has two terminals, the emitter and the collector. The device has a base, but typically it has no lead. Instead, the device is built so that when the base is exposed to light, it will cause the emitter–base junction to conduct. When light strikes the base, it causes ionization, which simulates base current flow. Therefore, the transistor conducts between emitter and collector. The primary advantage of a phototransistor is its very high sensitivity over a photodiode. It will conduct even with a small amount of light applied to the base. The transistor essentially provides amplification so that small light levels can control a large current.

A typical closed-loop control circuit using a photoelectric cell is illustrated in Fig. 12.11. This circuit will automatically turn a light on when it gets dark and turn the light off when it is light again. Note that a photoresistive cell is connected as part of a voltage divider with resistor R_1. The DC voltage from this voltage divider is applied to one input of an op amp comparator. The DC reference input to the comparator comes from a voltage divider made up of R_2 and R_3. The potentiometer can be used to adjust the DC reference voltage or set point. The output of the comparator drives a switching transistor Q_1, which will turn the relay K_1 off or on. This, in turn, operates the light.

When the photoresistive cell is exposed to light, its resistance will be very low. Therefore, the voltage from the voltage divider will be low. It will be less than the DC set point voltage and the comparator will not be triggered. The output of the comparator will be a negative voltage, which will reverse bias the

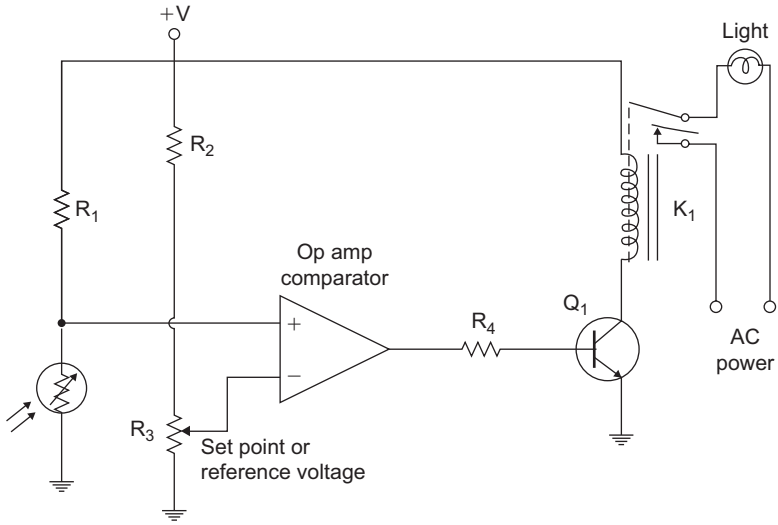


FIGURE 12.11 Simple off/on photo control circuit. Light turns on automatically at dark and off when light is present.

emitter–base junction of the transistor and keep it turned off. As soon as it gets dark outside, the resistance of the photocell will increase. This will cause the voltage divider output to increase. At some point, the voltage will be higher than the set point voltage, causing the comparator to switch. This applies a positive voltage to the transistor base, turning it on, and then turning on the relay and the light. The light will remain on as long as the photoconductive cell is in the dark. But as soon as light shines on the photocell, the voltage divider output voltage will drop, thereby triggering the comparator and turning off the transistor, the relay, and the light bulb. By adjusting the reference or set point voltage with potentiometer R_3, the triggering point can be varied, so that the light will be turned off or on at the desired level of ambient lighting.

This same basic concept can be used to produce a variety of industrial control operations. For example, you could use the circuit as an entry or intrusion detector. Shine a light on the photocell. If someone or something comes between the light and photocell, the circuit will trigger and the relay could then be used to operate a bell or buzzer or light.

Another example of a photoelectric controller is a tachometer circuit used for measuring the speed of a rotating shaft. Fig. 12.12 shows a small, plastic wheel connected to the shaft of a motor. There are alternate clear and opaque areas on the disk. The disk is positioned so that it is between the light-emitting diode (LED) and the phototransistor. As the disk rotates, the dark opaque areas will block the light, while the clear areas pass the light from the LED to the phototransistor. When a clear area on the disk passes, the LED light will shine through it, hitting the phototransistor, and turning it on. When a dark area

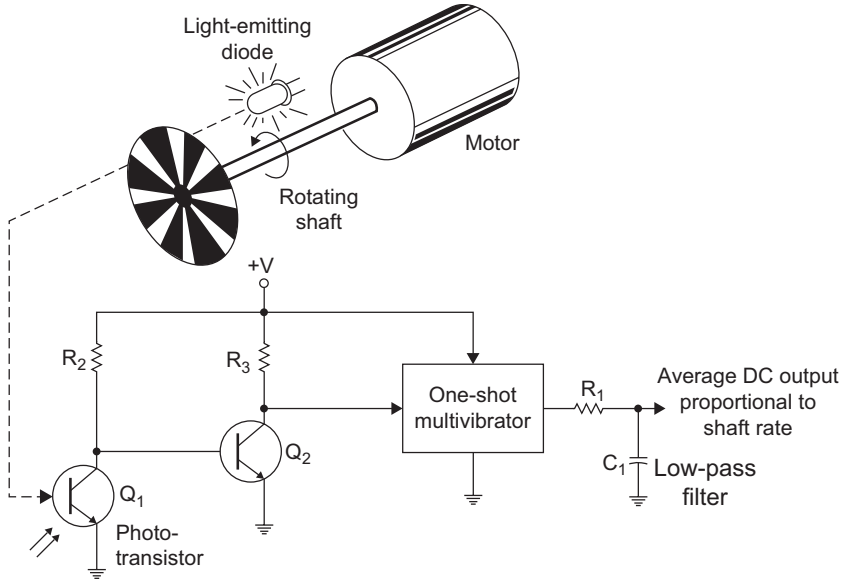


FIGURE 12.12 Simple tachometer circuit using phototransistor to create pulses that are averaged into a DC voltage proportional to speed.

passes, the light will be blocked and the phototransistor will turn off. The rapidly rotating disk will cause the transistors to turn off and on very rapidly. This rapid conduction and nonconduction of the phototransistor causes a series of pulses to occur at the output of Q_2. These pulses are used to trigger the one-shot multivibrator.

The one-shot multivibrator produces a series of fixed, amplitude-width pulses. These are applied to an RC low-pass filter made up of C_1 and R_1. This filter will average the pulses into a DC voltage. This output voltage is proportional to the motor speed. If the speed of the motor should increase, the pulses occur at a more rapid rate. This means that the pulses occur closer together, and thus the average voltage across C_1 goes up. A DC voltmeter connected to the output can be used to indicate the speed. At low speeds, the meter indication will be low, while at high speeds it will be high. The meter dial itself can be calibrated in terms of revolutions per minute (rpm), thereby giving an accurate speed indication.

Flow Sensors

These devices have liquid or gas pass through them and measure the amount of flow in gallons per minute or other measure. They develop an output voltage proportional to flow rate.

There are too many other sensors to catalog here but in most cases there is a sensor to convert any physical variable into a voltage to be measured.

OUTPUT DEVICES

An output device or an *actuator* is the thing that is most often controlled in a control system. The two most common types of actuators are relays and motors. There are many types of both.

Relays

A relay is an electromagnetically operated switch. A typical relay, and its schematic symbol, is illustrated in Fig. 12.13. Its main components are a magnetic coil and a set of switching contacts. With no current applied to the coil, the spring keeps the armature pulled down, so that the contact arm makes connection with

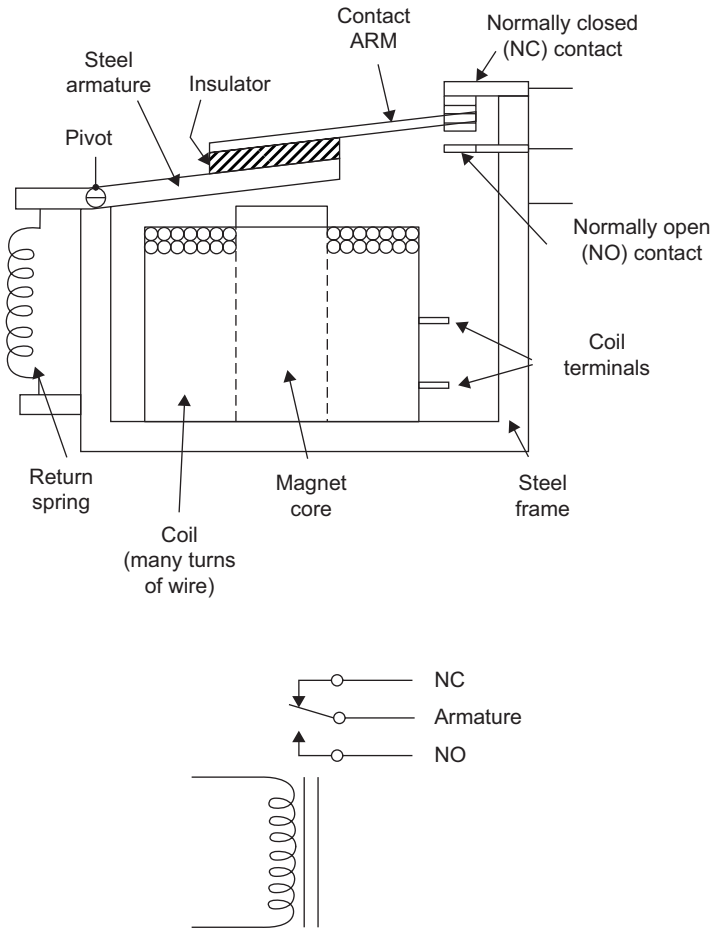


FIGURE 12.13 Cross-sectional view of typical relay showing major components and schematic diagram.

the upper, normally closed (NC) contact. When current is applied to the coil, a magnetic field is produced. This magnetic field attracts the steel armature, opening the upper contact, and closing the lower, normally open (NO) contact. The contacts form a single-pole, double-throw (SPDT) switch. When power is disconnected from the coil, the magnetic field ceases, and the contacts return to their initial state because of the spring.

Relay coils are designed to be operated from either AC or DC. The contacts are small circular disks of silver or tungsten. These materials are chosen because they will handle a large amount of current with minimum burning, arcing, and pitting.

The various kinds of switching contacts used in relays are illustrated in Fig. 12.14. NO contacts are referred to as *form A*. Applying power to the coil closes the contacts. NC contacts are referred to as *form B*. When power is applied to the relay coil, the contacts open. SPDT switching contacts are referred to as *form C*. When power is applied to the relay coil, the contact arm moves from contact A to contact B. Form C contacts are usually of the break-before-make variety. That is, contact A opens before the arm touches or "makes" contact B.

Sometimes you will hear the expression that a relay has been "picked" or "picked up." This means that power has been applied to the relay coil, and its contacts have been moved according to their function, and switching of a circuit has occurred.

Most relays usually have more than one set of contacts, so that multiple switching operations can be performed simultaneously. The various contact arms are ganged together so that they operate together when power is applied to the coil. A common configuration is two form-A contacts ganged to form a double-pole, single-throw (DPST) relay. Putting two form-C contacts together on the same relay produces a double-pole, double-throw (DPDT) relay.

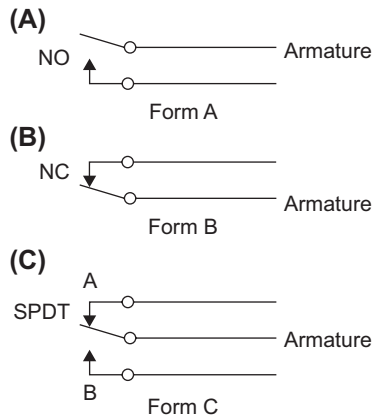


FIGURE 12.14 Common relay contacts. (A) Form A, (B) form B, and (C) form C.

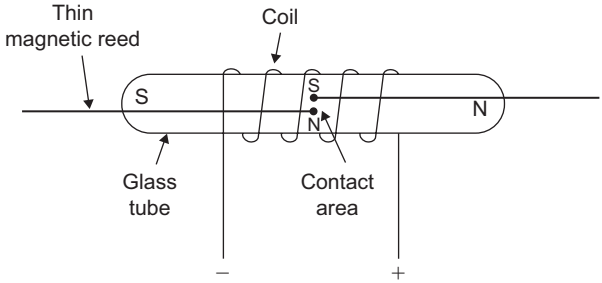


FIGURE 12.15 Reed relay.

Another widely used type of relay is the *reed relay*, illustrated in Fig. 12.15. The heart of the reed relay is a reed switch that consists of two thin, metallic, reed contacts sealed in a glass tube. The reed contacts are made of a magnetic material, so that they will be magnetized when a magnetic field is applied to them. A coil consisting of many turns of fine wire is wound on a form and placed over the reed switch. When power is applied to the coil, a magnetic field is produced. This magnetic field magnetizes the two reeds as if they were bar magnets. One end of each reed will have a north pole and a south pole. The reeds are positioned so that the north pole of one will attract the south pole of the other. Remember, magnetic theory says that unlike poles attract, whereas like poles repel. The result is that the contacts will move toward one another and touch, making a good electrical connection. When power is removed from the coil, the contacts become demagnetized and spring apart. The reed relay will also operate by moving a permanent magnet near it. When the magnet is near, the contacts will close. This is a common way to sense open windows or doors in a home security system.

The contacts on reed relays cannot handle as much power as the contacts on conventional relays because they are smaller. As a result, they are used only in lower current power applications. However, the contacts on a reed relay open and close faster than those of a larger standard relay. Reed relay contacts can open and close in a few hundred microseconds, while standard relays require many milliseconds to open or close because of the larger contacts and the related structures that must be moved.

Relays are used in two basic ways in industrial control:

1. To control a larger current with a smaller current.
2. For remote control.

Let us examine the use of a relay for controlling a larger current with a smaller current. A good example of this is the starting system in your car. A large, heavy-duty DC motor is used to spin the flywheel on the car's engine to start it. This motor draws a current of hundreds of amperes. To turn the engine

and start the car, the battery must be connected to the starter motor. This could be done directly by having the ignition switch connect the battery to the motor. However, this switch would have to have very large contacts to handle the high current. Such a switch would be large and expensive to build. The large heavy wires from the battery to the motor would have to be lengthened and brought up into the car.

A better solution is to use a smaller ignition switch to control the current applied to a relay coil (see Fig. 12.16). The relay coil draws considerably less current than the motor; therefore, the switch contacts need not be large or expensive. The switching contacts on the relay are much larger and will carry the high motor current. When the ignition switch is turned on, its contacts close, applying current to the relay coil. The form-A relay contacts close, connecting the battery to the starting motor. When the car starts, the ignition switch is released, the relay drops out, and the starter motor shuts off.

Another application of a relay is remote control. Again, the starting system of a car is a good example. The load to be controlled, in this case the starter motor, is located remotely from the ignition switch. If the ignition switch were used to apply current to the motor, long wires would be required to connect the battery, the motor, and the switch. Heavy wire conductors would have to be used to carry the high current. The longer the interconnecting wires, the higher the resistance of the circuit. While large conductors have minimum resistance, when high current flows through them, voltage drops still occur. The voltage dropped across the interconnecting lines subtract from the battery voltage available for the motor. The voltage drops might be excessive, unless very large, expensive, and inconvenient conductors are used.

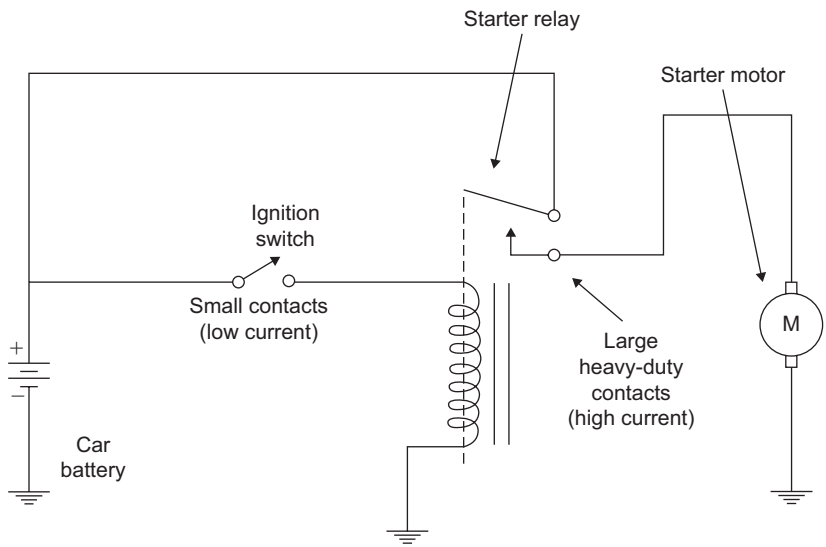


FIGURE 12.16 Controlling a large current with a smaller current with a relay.

To eliminate this problem, a remote relay is used. The relay itself is located near the starter motor and the battery. In this way, the interconnecting leads can be kept short, thereby minimizing voltage drops. Since the relay operates from very low current, longer interconnecting wires can be used to attach it to the ignition switch without noticeable voltage drops.

In some industrial control applications, the load to be operated is located at extreme distances from the switch used to control it. The current controlling the device does not have to be passed through very long conductors if a relay is used. Small conductors running to the switch remotely from the load control the relay while the relay turns the load off and on.

Relay contacts stay closed (or open) as long as power is applied to the coil. This means that the switch operating the relay coil must be kept closed if the relay is to remain actuated. There are applications, however, where it is desirable to use a momentary contact switch to operate the relay. An example is a pushbutton that, when depressed, causes contacts to be closed and power to be applied to the relay. When the button is released, a spring causes the contacts to open. With such an arrangement, the relay will close momentarily while the button is depressed, but will drop out when the button is released. The objective is to cause the relay to latch into its actuated position when the coil is momentarily pulsed. Such a relay is called a *latching relay*. Some latching relays use a mechanical arrangement on the armature to cause the contacts to latch closed when the coil is momentarily pulsed.

A relay can be made to latch electrically if it has an extra set of contacts. A typical latching circuit is shown in Fig. 12.17. This relay has two sets of form-C contacts that operate simultaneously. The lower set of contacts is used to operate the load. The upper set of contacts is used to automatically latch the relay once it is pulsed. Switch S_1 is a NO momentary contact pushbutton that is used to apply power to the relay coil. Depressing the button causes the relay coil to operate, closing the contacts. The lower set of contacts operates the load as desired. The upper set of contacts applies the power to the coil. Thus, when pushbutton S_1 is released, the circuit to the relay coil remains closed through the upper-latching contacts. To turn off the circuit, NC pushbutton S_2 must be depressed. This breaks the relay coil circuit, removing power. The relay drops out, opening the load contacts and the latching contacts.

While many relay coils are operated by mechanical switches, others are operated by a transistor. A typical transistor-controlled relay circuit is shown in Fig. 12.18. The transistor is operated as a switch. When the base is grounded through contact B on S_1, the transistor is cut off and acts as an open switch. Therefore, no current flows in the relay coil. When a voltage is applied to the base resistor, through contact A on S_1, the transistor saturates, acting like a very-low-resistance or "on" switch. Current flows through the relay coil, operating the contacts. Removing the base current from the transistor turns the transistor off, terminating current in the relay. With this arrangement, an even smaller current can be used to control the already small relay current. A base current, of only microamperes, is sufficient to cause the transistor to operate.

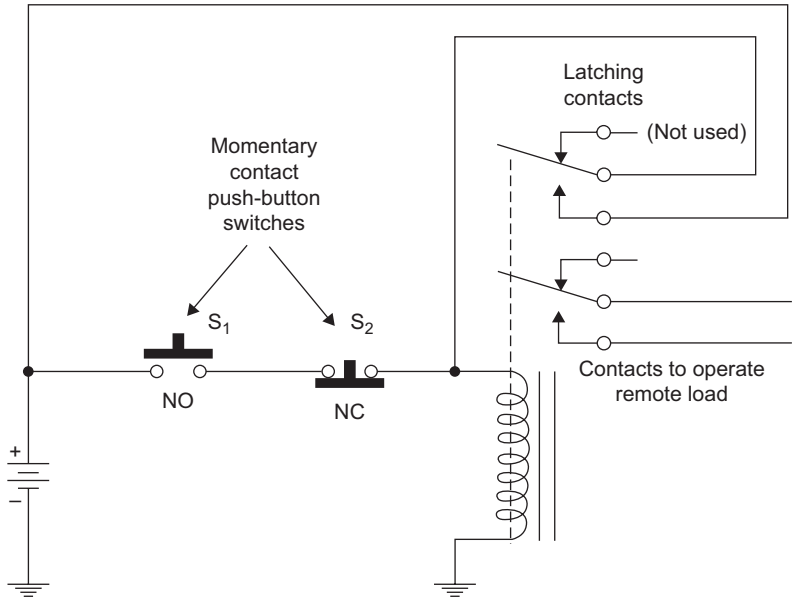


FIGURE 12.17 Latching a relay with its own contacts.

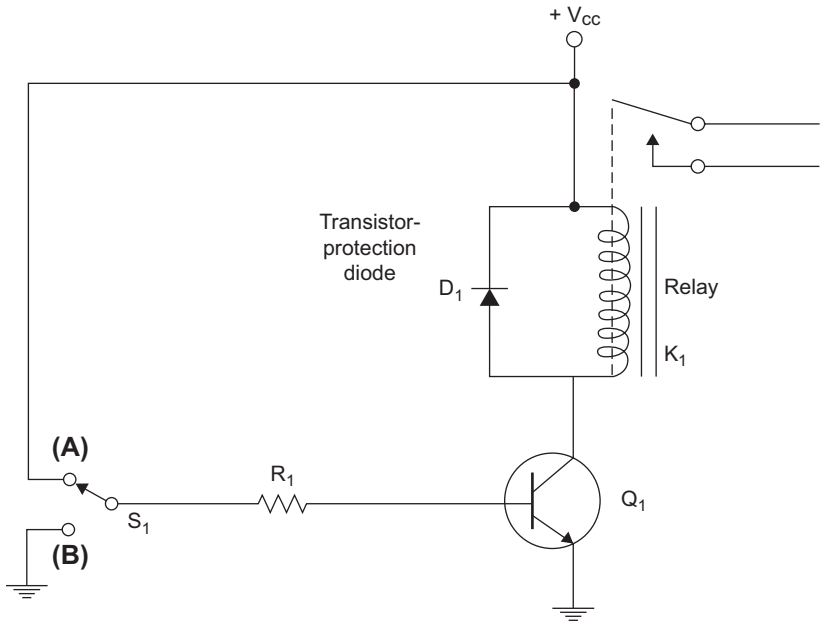


FIGURE 12.18 Operating a relay with a transistor is a common application. The diode protects the transistor when power is removed from the relay coil.

In the circuit of Fig. 12.18, when base current is removed from the transistor, the transistor will cut off. When current through the relay coil ceases, the magnetic field around it collapses. In doing so, the magnetic field induces a very high voltage in the relay coil. This very high voltage will be applied to the collector of the transistor. This voltage could be as high as several hundred, or even thousands, of volts, depending on the relay coil. Such a high voltage will damage the transistor. To protect the transistor against such occurrences, some kind of voltage spike eliminator or surge suppressor must be used across the relay coil. A commonly used protection device is a silicon diode D_1, as shown in Fig. 12.18. When current is applied to the relay coil through the transistor, the diode is reverse biased and has absolutely no effect on the circuit. When the transistor turns off, the high voltage will be inducted into the coil with the polarity reversed from the supply voltage V_{cc}. This causes the diode to become forward biased and conduct. Thus, the diode effectively shorts out the high voltage spike, protecting the transistor.

Solenoids

A solenoid is a device that produces linear motion with an electromagnetic coil (see Fig. 12.19). A magnetized steel rod called a plunger is inserted into a coil of wire. When a voltage is applied to the coil, a magnetic field is produced. It interacts with the magnetic rod producing attraction and/or repulsion that causes the rod to move into or out of the coil. The rod is usually physically constrained in one or both directions, and is often spring loaded so that it always returns to the same place when power is removed.

Solenoids produce linear motion. They are usually connected to a lever or ratchet mechanism that produces other forms of motion including rotation. Solenoids are also used in valves to turn off the flow of a liquid or gas. By continuously controlling the current in the coil, the rod may also be precisely set to some position other than off or on. This effect is used in valves to continuously control the opening.

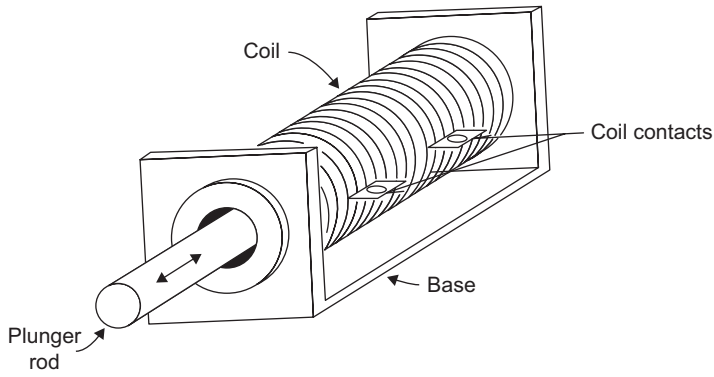


FIGURE 12.19 A solenoid produces linear motion using magnetic principles.

Motors

A motor is a device that converts electrical energy to mechanical energy. The mechanical output is typically the rotation of a shaft. That rotation can then be used directly or converted into other mechanical forms with levers, gears, ratchets, or cams. There are dozens of different motor types but most are categorized as either DC or AC.

Motors: Billions and Billions Sold and Used

Motors are one of those devices we take for granted. We use them every day but do not realize it. Most motors are hidden but do an enormous amount of physical manipulation. In industry, motors drive machine tools, conveyer belts, pumps, and other mechanical systems. Elevators use big motors.

At home, motors are everywhere. Just think a minute and try to identify all the motors you have in your home and in your car. All of your appliances have motors, such as the washer, dryer, dishwasher, and HVAC units. There are motors in your mixers, blenders, and can openers. Shavers and hair dryers have motors. An analog clock is a motor. Then there are the motors in your electronics. In a PC or laptop, there are the fan motor and the ones in your hard disk and CD drives. Your printer, scanner, and copier and fax machine have motors. Your DVD player and CD player have multiple motors.

Then in your car is the starter motor, as well as the motors for windows, seats, mirrors, and windshield wipers.

Can you name some others?

DC Motors

A DC motor operates from a DC voltage source like a battery or power supply. It is made up of a magnet and a rotating coil. When a current is applied to the coil, it forms an electromagnet. The magnetism of the coil interacts with the magnet field, producing rotary motion. The magnet is commonly a permanent magnet in smaller DC motors but an electromagnet in larger motors. In the larger motors, a special field coil is energized with DC voltage as well to create the magnetic field.

The main specifications of a motor are its horsepower rating, speed, and torque. Speed and torque are controlled by the amount of current flowing in the coil and/or the strength of the magnetic field. Increasing the voltage applied to the motor usually causes speed and torque to increase. Some kind of electronic control circuit is usually involved to set the speed to the desired value. A variable resistor in series with the motor will control its speed, but usually more complex electronic circuits are involved.

Incidentally, the direction of rotation is determined by the polarity of the DC voltage. Reversing the polarity reverses the magnetic field, thus changing the direction of rotation. Fig. 12.20 shows a neat circuit used to change the direction of

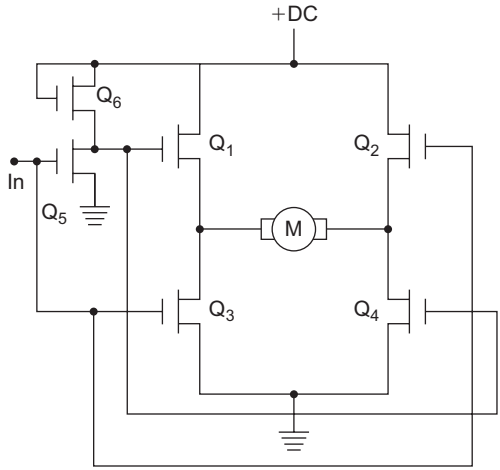


FIGURE 12.20 Using an H-bridge circuit to reverse the current flow and direction of rotation in a DC motor.

rotation of a DC motor. This is called an H-bridge and is made up of MOSFET switches. Q_2 and Q_3 are turned on by a positive input voltage IN. Q_5 inverts this voltage to zero, which keeps Q_1 and Q_4 off. Therefore, current (electrons) flows from ground through Q_3 through the motor (M) from left to right through Q_2. Setting the input to zero turns off Q_2 and Q_3 and turns on Q_1 and Q_4. Now current flows from ground through Q_4 and the motor from right to left and then through Q_1. This changes the direction of the motor with just a simple on/off input control voltage.

Most DC motors rotate too fast for many applications. A typical speed range is 1000–10,000 rpm. To achieve lower speeds, the motor is used in conjunction with a gear box or pulleys.

A special type of DC motor is the *stepper motor*. This is a DC motor driven by two DC pulse signals. The pulses operate coils or windings that produce a rotating magnetic field. A permanent magnet rotor interacts with the rotating magnetic field to produce motion. The interesting characteristic is that the rotation occurs in increments or steps instead of a continuous rotation as with a standard DC motor. Depending on the number of windings and coils and elements on the rotor, the increments usually vary in increments of 22.5, 18, 15, 7.5, or 3 degrees or smaller. The stepper motor therefore permits very precise positioning. Yet it can be rotated at several thousand rpm if needed.

AC Motors

AC motors usually operate from a 50- or 60-Hz power line. Again the rotation is produced by interacting magnetic fields. The speed of rotation is fixed by the number of coils and magnet poles inside the motor. That speed is also often higher than needed, so gears and/or pulleys are used to drop the speed to the desired value.

To change the speed of an AC motor, you must vary the frequency of the AC voltage applied to it. This means that you cannot operate the motor directly from the AC power line if the speed must be changed. Instead, you must use a so-called AC drive. This is a box of electronics that generates a variable frequency AC voltage to apply to the motor. An AC drive takes the AC line input and uses semiconductor switches to produce an AC signal at a different frequency.

Other Actuators

Besides motors, solenoids, and relays, there are a variety of different controlled devices. Valves are common device. Valves are used to turn the flow of a liquid or gas on or off. Proportional valves very carefully regulate the amount of flow.

Other devices are hydraulic or pneumatic devices. Hydraulic devices use oil in cylinders to provide mechanical force where needed or position something mechanically. Pneumatic cylinders work with compressed air to apply force or control the position of a device.

THYRISTORS

Many industrial switching circuits are implemented with MOSFETs designed for high voltage and high power. You will sometimes hear these devices called *insulated gate field-effect transistors* (IGFETs).

Other power-switching devices are also widely used, especially thyristors. A thyristor is a semiconductor device used for switching purposes in industrial control. Like the relay, it is used to apply and control electrical power to motors, heating elements, lights, and other loads in industrial applications. In many applications, thyristors replace relays. A thyristor acts as a switch, but because of its solid-state nature, is far faster in switching than a relay. There are three basic types of thyristors: silicon-controlled rectifiers (SCRs), triacs, and diacs.

Silicon-Controlled Rectifier

The SCR is a three-terminal thyristor that acts like a silicon rectifier diode whose conductor is controlled by an input current. The schematic symbol for an SCR is shown in Fig. 12.21. The symbol is similar to that of a diode with a cathode and an anode. Note that the third element of the SCR is known as the gate. The SCR will conduct current between cathode and anode, but only if the proper control current is applied to the gate. The gate must be made positive with respect to the cathode for the SCR to conduct. When conducting, the SCR acts like a closed switch. The voltage drop across the cathode and anode will be approximately 0.7–1.8 V, depending on the size of the SCR and how much current is flowing through it. When the cathode and anode are reverse biased, current will not flow through the device.

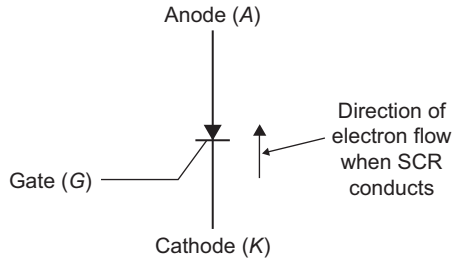


FIGURE 12.21 Schematic symbol of an SCR.

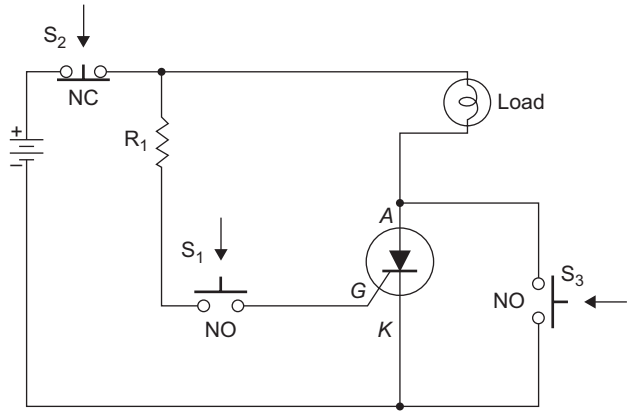


FIGURE 12.22 Circuit that shows how an SCR is turned on and off.

Thyristors, like relays, are generally used to control a larger current with a smaller current. Fig. 12.22 shows how an SCR is used as a switch to apply DC power to a light bulb. The load could also be a motor or heating element. The DC voltage is connected so that the cathode and anode of the SCR are forward biased, but no current will flow through the device until a current is applied to the gate. This is done with the switch S_1. With the switch open, no current flows in the gate. Closing the switch, however, applies a positive voltage to the gate through resistor R_1. This causes the SCR to turn on. When it conducts, it acts as a low-resistance "on" switch and the light bulb goes on. At this point, switch S_1 may be opened. It is not necessary to maintain current in the gate for the device to continue to conduct. The gate current only needs to be momentary, for it is only required to turn the device on. The device remains on like a latching relay that has been pulsed.

The gate element is only used to turn the SCR on. Removing gate current will not turn the device off. To cause the SCR to stop conducting, the circuit must be broken. This can be done with a momentary contact, NC pushbutton, in series with the circuit, like S_2 in Fig. 12.22. Depressing this pushbutton will break the circuit, stopping the current in the SCR, and the

light bulb will go off. To turn the bulb back on, S_1 must again be depressed to apply gate current momentarily.

Another way to stop conduction is to momentarily short around the SCR, as shown in Fig. 12.15. When switch S_3 is closed momentarily, current will flow through it and the bulb, bypassing the SCR. The current in the SCR will drop to zero. When switch S_3 is opened, the circuit will be off.

While SCRs are sometimes used to control DC power, in most applications they are used to control AC. Fig. 12.23A shows the SCR used to apply AC to a light bulb. If switch S_1 is closed, gate current will be applied to the device. The device, however, will only conduct when the anode is made positive with respect to the cathode. This, of course, occurs when the applied AC voltage has the correct polarity. Since the SCR operates as a rectifier diode, current will only flow through the device on the positive half-cycles of the sine wave. The current through the light bulb will be a pulsating DC, as illustrated in Fig. 12.23B. The brightness of the lamp will depend on the average amount of current flowing.

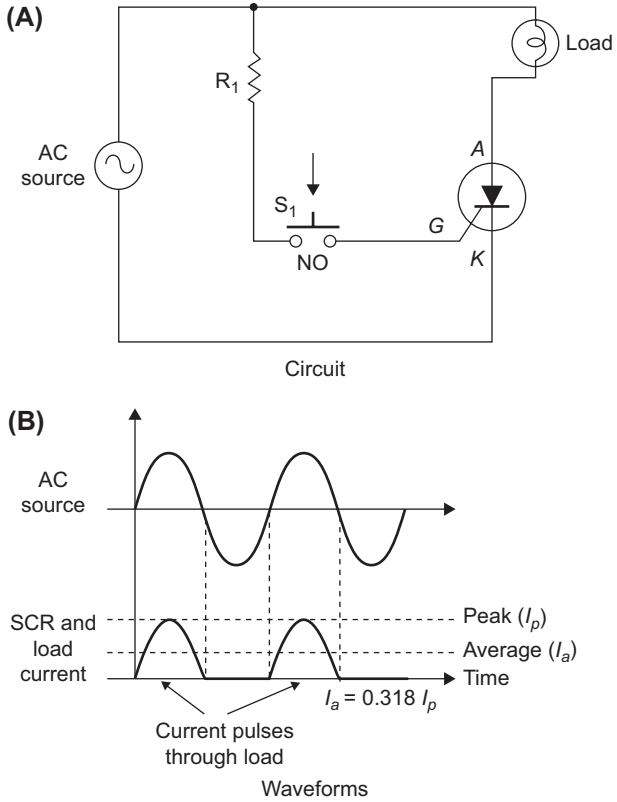


FIGURE 12.23 Using an SCR to control power to a load using AC. The SCR rectifies the AC.

The average amount of current through the light bulb, or other load, can be controlled by using the gate element. Various electronic circuits are used to adjust the time when the SCR turns on. By turning on the SCR at the appropriate time in the positive half-cycle, the duration of the current flow can be controlled. The longer the current is allowed to flow, the higher the average current in the load. By changing the control point, the brightness of the bulb can be varied.

Diac

A diac is a two-terminal semiconductor device that conducts in either direction when a voltage of a specific level is exceeded. This voltage is called the *triggering voltage*. Typical diac triggering voltages are in the 20- to 45-V range. The diac is used as a triggering device for SCR and triacs as it determines when the device will conduct or cut off.

Triac

A triac is another three-terminal thyristor. Its operation is similar to that of an SCR, but the triac will conduct in either direction. The schematic symbol for the triac is shown in Fig. 12.24. Current will flow from main terminal 1 (MT1) to main terminal 2 (MT2), or from main terminal 2 (MT2) to main terminal 1 (MT1), depending on the polarity of the voltage applied, and if the gate triggers the device on.

An approximate, equivalent circuit of the triac is shown in Fig. 12.25. Here, two SCRs are connected back to back with their gates connected together. Current can flow in either direction, depending on whether D_1 or D_2 conducts. Of course, SCR conduction depends on whether a gate-triggering current is applied. Triacs, like SCRs, are used primarily to switch AC voltage to a load. If gate current is applied continuously, the triac will conduct in both forward and backward directions, causing both positive and negative half-cycles of the AC to be applied to a load.

Fig. 12.26 shows a circuit used for light-dimming purposes. The load is a light bulb. An RC phase shifter and diac-triggering device are used on the gate of the triac. Assume that the diac has a triggering voltage of 30 V. If the voltage

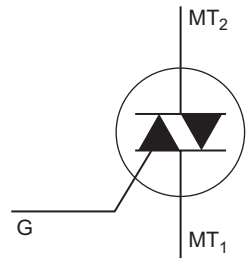


FIGURE 12.24 Schematic symbol for triac.

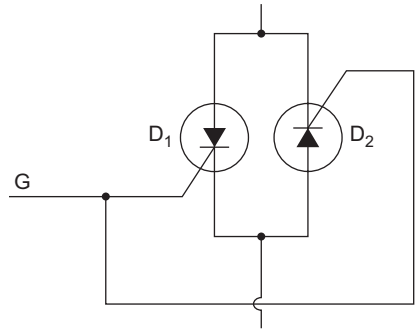


FIGURE 12.25 Equivalent circuit of triac shown with SCRs.

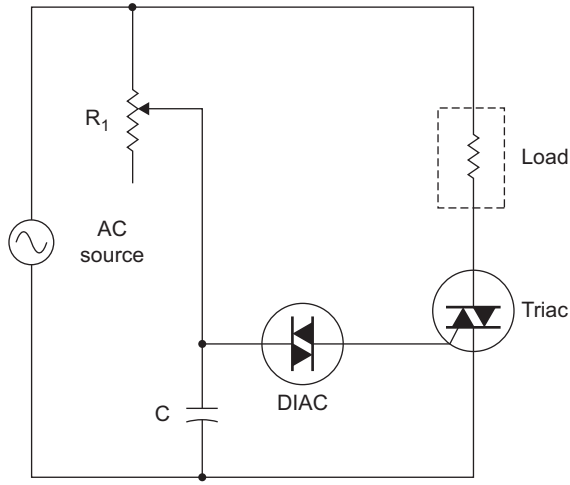


FIGURE 12.26 Lamp dimmer circuit using RC phase shifter and diac to control current in the load.

across the diac is less than 30 V, it will not conduct. As soon as the 30-V point is reached or exceeded, the diac rapidly conducts and fires the SCR. Keep in mind that the diac is a bidirectional device and that current will flow through it in either direction if the bias voltage in either direction exceeds the triggering voltage level.

The triac will conduct on both positive and negative half-cycles of the applied AC. The phase shifter made up of R_1 and C will set the triggering delay. It will determine at what point in the AC cycle the diac will fire and apply gate current to the triac. Fig. 12.27 shows the waveforms at two different phase-shift points in the circuit. Note that current flows through the load in both the positive and negative half-cycles, but the duration of current flow depends on the point where the gate triggers. In Fig. 12.27, the average current through the load will be relatively high at a 60-degree phase shift, and the bulb will be

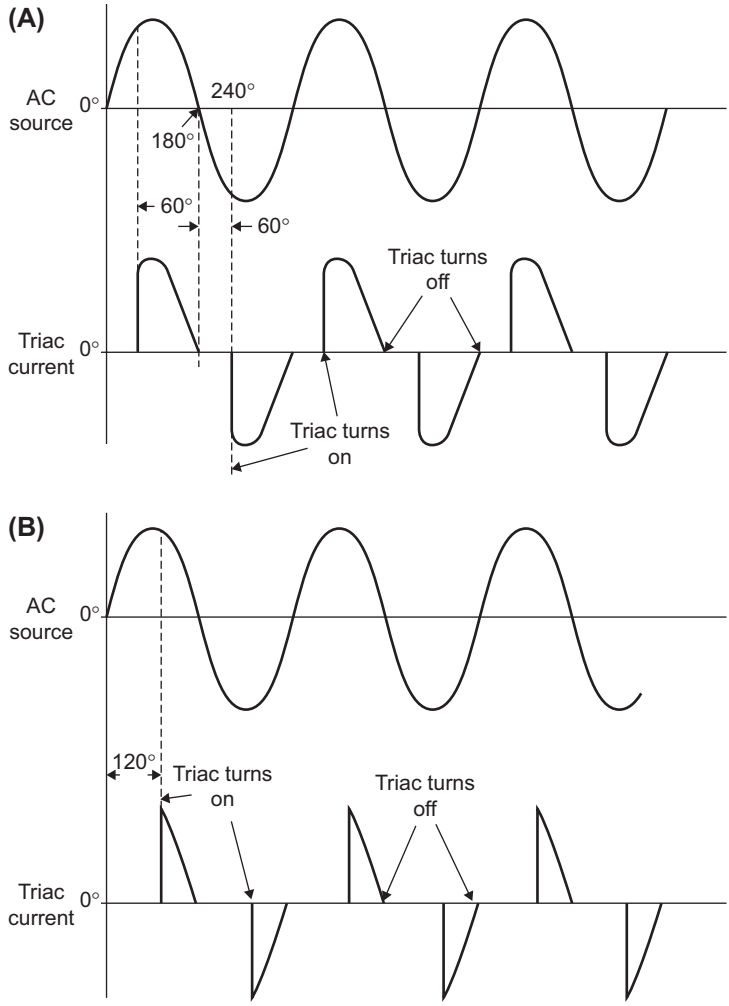


FIGURE 12.27 AC waveforms in a lamp load controlled by a triac. (A) Waveforms with triggering at 60 degrees, (B) waveforms with triggering at 120 degrees. The longer pulses produce higher average current in the load.

bright. At 120 degrees, the triggering point is late in each half-cycle, allowing only a small amount of current to flow through the bulb. The bulb, therefore, will glow dimly. Adjusting R_1 will allow the brightness of the bulb to be varied from nearly full on to full off. This is the circuit normally used in household and industrial light dimmers.

This same circuit can be used to control the speed of AC motors. In connecting a hand drill as the load, for example, R_1 will vary the speed of rotation.

Triacs are also widely used as solid-state relays.

PROGRAMMABLE LOGIC CONTROLLERS

A very popular type of controller used in industry and process control is a specialized computer called a programmable logic controller (PLC), or programmable controller. It uses sensors to monitor physical variables and generates output control signals to operate heating elements, motors, pumps, solenoids, and other devices. The PLC, however, contains a microprocessor that can be programmed in a special language that permits the PLC to be customized to the particular control function. In this way, a standard PLC can be programmed and configured for virtually any application. The PLC is by far one of the most popular and versatile control devices in use in industry.

The main function of a PLC is factory automation. It is a versatile special-purpose computer that can be quickly and easily reconfigured to meet changes and additions in factories, plants, and other operations that routinely need to control and sequence various machines and processes. While an embedded controller or personal computer could be used in some operations, they are harder to program and apply and are less flexible when rapid changes are needed. Furthermore, these common microcomputers are not designed for the factory environment. But PLCs are rugged and hardened against the harsh environment of most factories and plants. They can withstand the temperature ranges, vibration, and dirty conditions usually existing in a manufacturing or process control setting.

Organization

A general block diagram of a PLC is shown in Fig. 12.28. It is like most other microcomputer diagrams but there are some differences. A microprocessor is at the heart of the design. This CPU is coupled to a ROM where a special control program is stored. This program implements the basic scan operational mode of

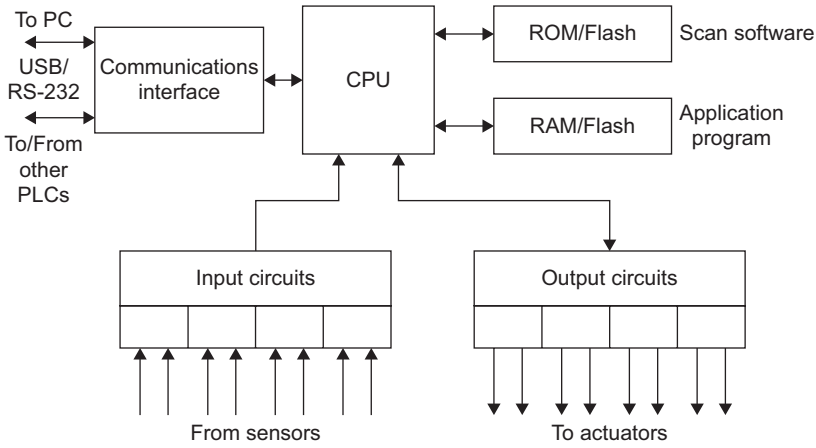


FIGURE 12.28 General block diagram of PLC.

the PLC. RAM is also available to store the application program. Flash memory may also be used in place of RAM.

The key to the PLC's versatility is its extensive I/O section. It has a variety of input and output modules. These are fixed in small, single-function PLCs, but in the larger more flexible units, the PLC is designed to accept a wide variety of separate I/O modules. These usually plug into a rack containing the main PLC unit and power supply. The different I/O modules let the user customize the PLC to the specific application.

Some examples of I/O modules are digital inputs and outputs with common logic levels or conditioned levels, analog input modules that accept analog signals from sensors, and analog output modules that generate analog outputs for controlling actuators of almost any kind. A huge variety is available. A communications interface is also available so that the PLC can talk to external devices such as a PC or other PLCs that are connected to form a larger control system. RS-232 and RS-485 serial interfaces are common as is USB. The program describing the operations to be implemented is developed on an external PC, and then downloaded to the PLC RAM or flash memory via the USB or RS-232 interfaces.

Operation

The general operation of a PLC is shown in Fig. 12.29. When the PLC is started, the internal operational program looks at the application program and interprets what is to be done. The sequence of operations is to first scan the inputs. The PLC looks at what the various sensors are doing. It gets a status

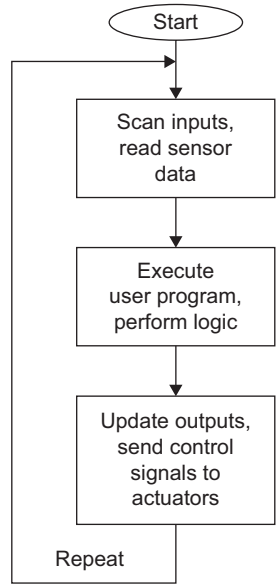


FIGURE 12.29 PLC operational scan cycle.

update from the application itself. The program then interprets what to do next based on the application program. It processes the input to determine what the outputs should be. Then it updates the outputs to carry out the application. Then the cycle repeats itself at a high rate of speed. The inputs are scanned and outputs are updated every 1 ms or so, slower or faster as the application requires.

A simple example is using a switch to turn on a motor. The switch contacts are connected to an input module by wires. Output wires connect to a relay that in turn is used to operate the motor. As the PLC is scanning, it sees that the switch is off, so it does nothing. But as soon as the switch is turned on, the next scan detects this new condition. The program then tells the CPU that if the switch is on, turn on the relay. An output signal is sent to the output module, which then actuates an external relay. The relay contacts then turn the motor on. If the switch is then turned off, the next scan detects this condition and causes the output to turn off the relay and motor.

Programming

As for programming, PLCs can be programmed in various ways. Most PLC vendors have special languages to do the programming. In some cases, standard BASIC or C languages may be used. One widely used approach is a graphical language called *ladder logic*. Ladder logic is the technology that the PLC replaced decades ago. Control systems were made with relays, and they were wired so the diagram looked like a ladder (see Fig. 12.30). The two vertical lines represent a DC or AC voltage source. Circuits are then connected between these two "rails," forming rungs on the ladder. The circuits are connections of switches, relays, and other components. The software allows the user to build the ladder logic program on the screen, while a translation program in the PC converts it into the binary code that the PLC can execute.

This particular circuit in Fig. 12.30 does the following: when the ON pushbutton is pressed, current is applied to relay coil 1CR through NC contacts of SW1. SW1 is a thermal switch whose contacts stay closed as long as the temperature is less than 300 degrees Fahrenheit (300°F). If the temperature rises above that level, the contacts open, thereby breaking the circuits. Relay contacts 1CR around the ON pushbutton latch the circuit on when the ON pushbutton is released.

In the next "rung" of the ladder contacts 1CR are on the relay. They close when the relay turns on. This applies voltage to a heating element. This current flows through the NC contacts of thermal switch SW2. A green light in parallel with the heating elements turns on to indicate the heater is on.

When the heater temperature reaches 200°F, SW2 opens, turning off the heater and the green light. As the heater cools, SW2 will then close again, applying voltage to the heater. The heater will then cycle off and on keeping its temperature near the 200°F value.

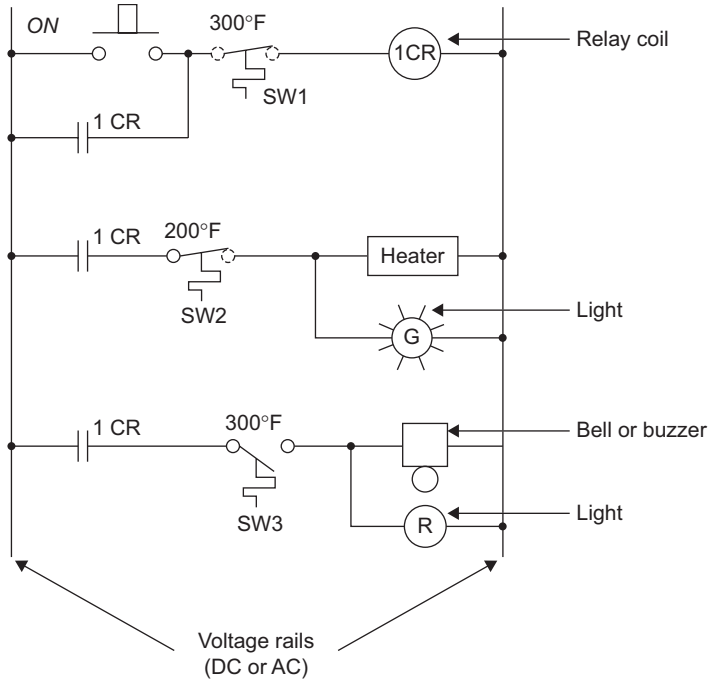


FIGURE 12.30 Sample ladder diagram and PLC application program.

If the temperature should rise above 300°F due to a failure of SW2 F, then SW1 opens. Relay 1CR is turned off, and its contacts open, releasing the latch on rung 1 and opening the circuit on rung 2. Thermal switch SW3 closes at 300°F, turning on a red light and ringing an alarm bell.

This example could be programmed with a graphical ladder logic program or with special commands and syntax of a traditional programming language.

In addition to being able do simple on/off tasks common to industrial control, special hardware in the PLC can also implement counters and timers so that external events can be counted and the sequencing of events can be programmed.

Data Acquisition Systems

A data acquisition system, often abbreviated DAQ, is a collection of circuits and equipment used for capturing data from multiple sensors when testing or monitoring conditions in a specific product or system. While testing automobiles or aircraft, it is common practice to measure multiple points in the target product to see how it performs to specifications or to detect problems. Common physical factors monitored include temperature, stress, pressure, humidity, mechanical position, liquid flow rate, and others related to the system. Industrial factories and process control plants such as refineries use DAQ to keep an eye on the state of the systems and its performance.

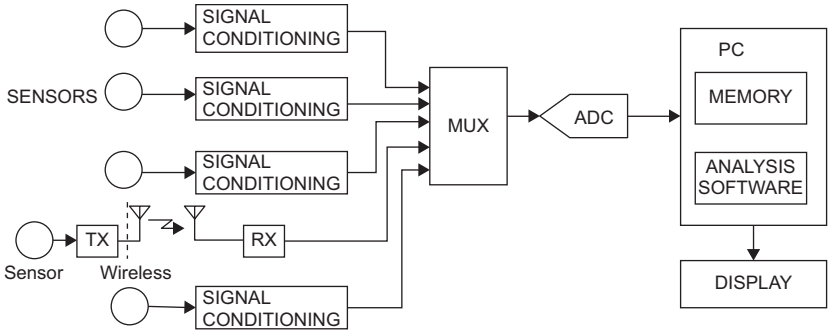


FIGURE 12.31 The key components and organization of a typical data acquisition system.

The main components of a DAQ are shown in Fig. 12.31. The inputs are from sensors that are usually connected by cables to signal conditioning circuits to prepare their outputs to be digitized. Signal conditioning includes amplification, filtering for noise, level shifting, or other corrections. In some applications the sensor may be far from the DAQ system in which case a wireless link can be established using Wi-Fi or other wireless technology.

The processed sensor signals then go to a multiplexer (MUX) that selects the sensor to be digitized and passes the signal along to an analog-to-digital converter (ADC) that samples the analog signal from the sensor and converts it to a stream of binary values, usually 8 to 16 bits long. Sampling rates are usually low, from several samples per hour to 1 MS/s. The resulting data words are then sent to a PC and stored in a file. The data can then be analyzed by software, used in analysis or converted into appropriate displays or graphs.

Project 12.1

Build a Robot

Robots are great examples of basic industrial control. While most industrial robots are usually manipulator arms, you can actually buy a mobile robot with wheels that can be programmed for motion and other functions. A wide range of kits are available. It is a great way to get familiar with sensors, a microcomputer controller, and various actuators. Typical inputs are switches, photo cells, temperature sensors, and common outputs are relays, lights, and motors.

Some recommended kits are those supplied by Lego and Parallax. Suggested websites to learn more follow:

Jameco: www.jameco.com
Lego Mindstorms NXT: www.mindstorms.lego.com
Parallax: www.parallax.com

Two magazines regularly cover robots from a hobbyist/experimenter viewpoint. These are *Nuts & Volts* and *Servo*. You may be able to find these at a newsstand; otherwise, go to their websites:

Nuts & Volts Magazine: www.nutsvolts.com
Servo Magazine: www.servomagazine.com

Project 12.2

Build a Feedback Control System

Feedback control systems as described in this chapter are very common in industrial electronics. This project lets you build one and demonstrate its operation. The basic circuit is shown in Fig. 12.32. A heating element, the 50 Ω resistor, is monitored by a thermistor. If the resistor gets too hot, the thermistor value will decrease and change the input voltage to a comparator. Voltage divider R_2-R_3 provides a 3.75 V set point to the comparator. The comparator will switch its output high turning on the MOSFET that, in turn, turns on a fan. The fan then cools the heating element. This causes the temperature to decrease and the thermistor value to go back up. The comparator switches again. Its output goes low turning off the MOSFET and the fan. The process then repeats automatically.

Build the circuit on your breadboarding socket. The parts list is given in Appendix B. You will need a 12 V supply for this project. An electronic supply is preferred but you can use two of your AA cell 6 V supplies in series. Use the long leads of the 50-Ω resistor to keep the body of the resistor away from the breadboarding socket as the resistor will get very hot and melt the plastic. Be careful as the resistor will burn badly. Physically place the fan several inches away from the resistor. The resistor should also be positioned within inches of the thermistor. Check your wiring to be sure there are no errors.

Apply power to the circuit. The 50 Ω resistor will draw 240 mA of current that will quickly deplete the charge on the batteries. Check the supply voltage with

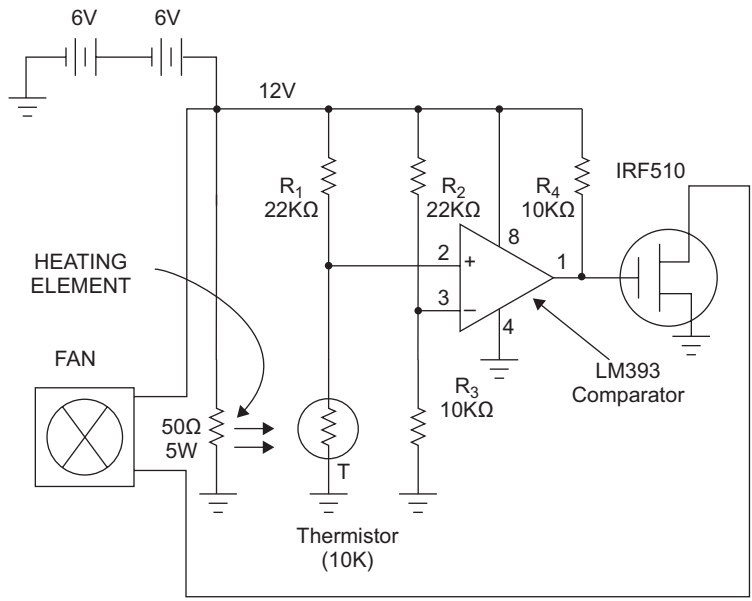


FIGURE 12.32 A simple feedback control circuit for temperature control.

Continued

Project 12.2—cont'd

your multimeter to be sure it is 12 V. Within a minute or so, the fan should come on. If it does not, reduce the distance between the resistor and the thermistor. Once the fan turns on, it will cool the resistor within a minute or so. The fan will then turn off. Experiment with the distances between the resistor and the fan and thermistor until the circuit works as described. Again, be careful as the resistor gets seriously hot. Turn off the power.

Chapter 13

Software, Programming and Electronics

Today, Most Electronics Is a Combination of Hardware and Software

In this Chapter:

- Micros in every electronic product.
- What is software?
- Types of software.
- Programming languages for embedded controllers.
- Learning to program.
- Micro projects.

INTRODUCTION

Electronics equipment used to be strictly hardware. However, over the years, vacuum tube circuits on a metal chassis gave way to transistors on printed circuit boards (PCBs) that, in turn, gave way to large-scale integrated circuits on smaller multilayer PCBs today. And that brings us to the key point of this chapter. That is, virtually all modern electronic products contain at least one microcontroller also known as an embedded controller.

The secret to making that microcontroller implement the product's functions is software. Those microcontrollers are simply pieces of hardware that have no specific application until they are given a program that dedicates the chip to the product's characteristics. This chapter picks up where Chapter 6 ends and then expands on the subject of software and introduces programming languages of interest. Projects using available microcontroller hardware and software are included.

SOFTWARE FUNDAMENTALS

Software is the general term that describes any program that tells a computer or microcontroller chip what to do. A program is a sequence of binary codes stored in memory that represent instructions that define specific operations that the

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00013-8
Copyright © 2018 Elsevier Inc. All rights reserved.

computer is capable of performing. The computer or microcontroller unit (MCU) is the visible hardware while the programs are the invisible magic ingredient buried in memory. The combination defines a specific product. In addition to the microcontroller and its programs are the external components and devices that serve input and output operations specific to the product. Our discussion here focuses on microcontrollers rather than general-purpose computers. Refresh your knowledge of microcontroller organization and operation in Chapter 6.

The microcontroller can perform almost any digital function from the simplest logic operation to a complex mathematical calculation. For many products, dozens of digital logic chips can be replaced by a single microcontroller. The only problem is that you have to tell the MCU to do what you want. And you do that by programming. A program is the sequence of instructions that detail the order in which you do the various processing steps that lead to your application. The microcontroller chip itself is a dumb piece of hardware waiting for its program. What this means is that today, designing an electronic product is as much about writing programs as it is building electronic hardware.

Software is the name given to all the programs that a processor uses for developing and executing a program. The program that implements your product's functions is the applications program. Other types of software used with the MCU are as follows:

Language—A programming language is a set of rules or syntax that defines how you tell the processor what to do. A language is the tool that you actually use to create your application program. It is a kind of shorthand code that lets you express the operations in simple terms.

Machine code—This is the binary words that represent the instructions of a program. It is what tells the MCU hardware what to do and when. Hex characters are commonly used instead of binary for programming clarity and simplicity.

Assembler—An assembler is a programming language based on the instruction set native to the MCU. It is a collection of terms called mnemonics that define specific hardware functions. A programmer uses the instruction terms to create a step-by-step program. It is the assembler that translates the assembler code into machine code.

Compiler—A compiler is the program that translates your program code into binary code that can be stored in the memory and used by the processor. Processors only understand binary code, but humans are not good with such code. So, you write your program in a language you can understand, and the compiler converts it to the code that the processor understands. The compiler is not used to execute the program.

Interpreter—An interpreter is a program that resides along with the application program in memory and executes the application program one line of code at a time. The interpreter translates the instructions of the language into machine code to be executed by the MCU.

Operating system—For large complex programs or for applications that require the processor to execute multiple programs at different times, you need a piece

of software that manages the multiple programs and operations. The operating system (OS) oversees things such as memory usage and access, timing, and I/O operations. Not all embedded controllers need an OS, just the more powerful ones with multiple functions. For example, most cell phones have an OS.

Editor—An editor is like a word processing program that lets you type in your program using the language syntax. You then save it as a file that the compiler or assembler uses to create machine code.

Integrated development environment (IDE)—This is a complete package of software tools that facilitates software development. It consists of an editor, languages, and compilers, as well as programs for testing and debugging your code.

Debugger—This is a feature of most IDEs that makes it easy to find problems in a program such as syntax errors, misused instructions, address conflicts, timing problems, and others.

Subroutines—These are short sections of code that perform a specific operation. It may be a math operation, some type of I/O process, or other function that is performed multiple times. You only write the subroutine once, and then access it when you need to do that operation.

Libraries—Many IDEs have libraries of subroutines that you can tap so you do not have to program common functions yourself. Subroutines shorten your development time and speed execution.

Source code—This is the program that you write with the editor and store in a file. It is then given to the compiler or interpreter.

Object code—This is the machine code that is the output of the compiler.

Programming Languages

There are dozens of languages used for programming embedded controllers. The more popular ones are assembly language and C. An older language BASIC is not widely used in industry, but it is popular for learning programming for microcontrollers. Here is an overview of each.

Assembly Language

Assembly language uses shorthand mnemonics such as three- or four-letter designations for the instructions that the processor can execute. Instead of programming with binary code, you use the mnemonics. In addition, you use names that you make up to identify variables, constants, memory locations, I/O ports, and other things normally referenced by a binary code. Following is what a simple assembly program looks like:

```
ORG $0000
LDAA FIRST
MUL SECOND
STA PRODUCT
OUT PORT 1
END
```

This program loads one number from a memory location given the name FIRST, multiplies it by another number in memory location named SECOND. It then stores the result in another memory location called PRODUCT. It next outputs the value to an I/O port called PORT 1. The ORG $0000 simply says to start the program whose first instruction is in memory location 0000, a hex address.

The software that converts the assembly language program to binary code is the *assembler*. The assembler gives actual binary assignments to the memory locations named as well as the instruction op codes.

BASIC Language

Some embedded controllers use a simplified version of BASIC. BASIC was invented before personal computers but then initially became the main language of personal computer programming. Microsoft still sells its Visual BASIC software for program development. BASIC is a very simple higher-level language that is easy to learn and use. The program created is then translated into binary code by a compiler. Alternately, the microcontroller runs a program called an *interpreter* that resides in memory and executes the program, a command at a time.

The following program is written in PBASIC, a simple version of BASIC used with an embedded controller called the BASIC Stamp made by Parallax. It uses a PIC microprocessor and stores a program in flash memory. The program causes an LED to flash off and on.

```
Do
    High 7
    Pause 500
    Low 7
    Pause 500
Loop
```

The first line tells the controller to make the output pin 7 on the microcontroller high or binary 1. The next command says pause for 500 ms or one half second. Next, pin 7 is made to go low or to binary 0 via the Low command. Pause makes it stay there for another 500 ms. Finally, the Loop command causes the program to loop back and repeat itself again and again. This is what is called a Do…Loop for repeating a program over and over again. The result is an LED that turns off and on at a 1000-ms (1-s) rate.

C Language

The C language is referred to as a higher-level language in that the various syntax and terminology of the language usually translates into multiple binary machine instructions. The C language lets you write the program in a more conversational or casual format using English instead of cryptic mnemonics and other terms. The language is a bit of a challenge to learn, but after that programming goes much faster. A compiler converts the C language program code into binary code.

A simple C program may appear like this:

```
#include <stdio.h>
#include "stdio_setup.h"

int main (void)
{
UartInit();
int x, y, z;
x = 38;
y = 57;
z = y – x;
printf("The difference is %d", z);
}
```

The #include statements tell the compiler to include instructions to accomplish some of the actions specified by the program. The int main(void) is something that must be included in all C programs. The UartInit() tells the compiler to set up an output port for the result of the program. An open bracket symbol indicates the beginning of the program. The next line identifies three integer values x, y, and z; 38 is assigned to x, and 57 to y. Then the difference between the two is designated z. Finally, the printf line accesses a subroutine that causes the expression "The difference to be printed is 19." The z value is substituted for %d indicator. Note that all lines of the program end with a semicolon. The end of the program is indicated by the close bracket.

PROGRAMMING

Programming is the process of solving a problem with a computer. Sometimes called coding, programming is a multistep process that involves identifying and defining the problem, developing a solution to it, and then preparing a sequence of instructions that solve the problem.

There are five steps in the programming process. These are as follows:

1. Problem definition
2. Solution development
3. Program coding
4. Program testing and debugging
5. Documentation

In problem definition, you state as clearly as possible what you want to accomplish. Typically it is best to make a written statement of the problem. By actually writing out what is to be accomplished, you will think through the problem more thoroughly. Making charts, tables, graphs, drawings, or the like is also useful. Define your inputs, define the desired outputs, and then outline the processing steps required. Thorough problem definition produces a solution faster and easier. This is the most important step in programming.

Once the problem has been defined, you are ready to develop a solution. It is virtually impossible to give you guidelines on how to do this. Developing the solution is really the creative part of programming. The best way to learn it is by actually doing some programming. The more problems you solve, the more creative and proficient you will become. In any case, developing the solution is best done when the problem has been clearly defined and when you have a good working knowledge of the MCU, its instruction set, and the programming language you are going to use.

The solution you develop is typically a step-by-step procedure. Each step in the solution will cause some part of the problem to be solved. A step-by-step sequence of procedures for solving a specific problem is called an *algorithm*. An algorithm may be a mathematical formula or just a recipe-like list of steps.

A useful tool in developing a solution to your programming problem and in preparing your algorithm is the *flowchart*. A flowchart is widely used by programmers to provide a visual or graphical presentation of the solution. Sometimes the solution is more easily seen or understood by blocking out a problem in graphical or visual form.

Flowcharts are made up of a number of simple symbols that depict typical computer operations. Fig. 13.1 shows the most commonly used symbols. The two most important symbols are the rectangle and the diamond. The rectangle simply specifies some particular operation. The diamond is a decision block. It usually asks a question that can be answered with a yes/no or true/false decision. This is the way most computers "think" or make decisions.

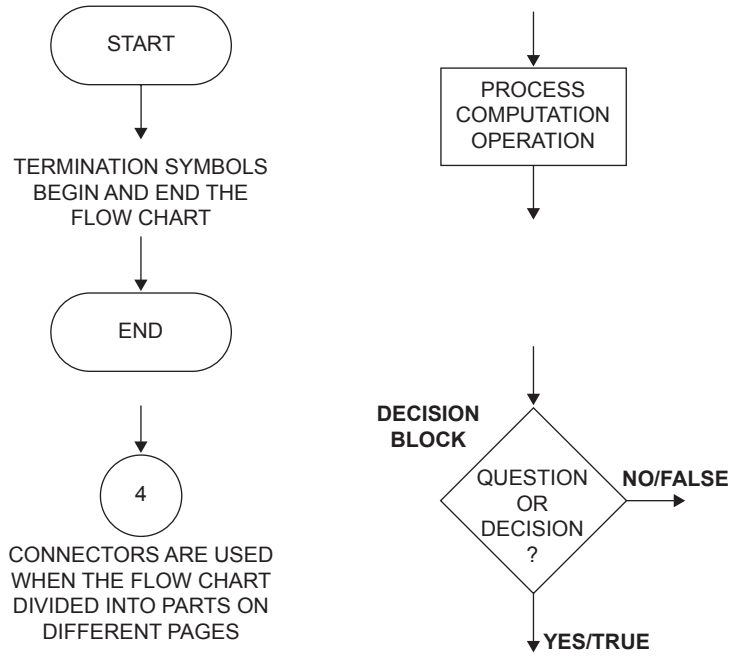


FIGURE 13.1 Flowchart symbols.

An example of a flowchart is given in Fig. 13.2. This flowchart represents the solution to a typical MCU problem. The problem in this example is to determine which of two numbers, A or B, is the larger. The algorithm is to subtract B from A. If the difference is positive, A is obviously greater than B. On the other hand, if the subtraction results in a negative difference, A is less than B, which means B is the larger. The flowchart illustrates the entire problem and solution.

One of the best approaches to programming a solution is to use *structured programming*. Also known as *top-down design*, structured programming is the process of taking the problem and partitioning it into modules that perform the major functions of the solution. In structured programming, you break down a

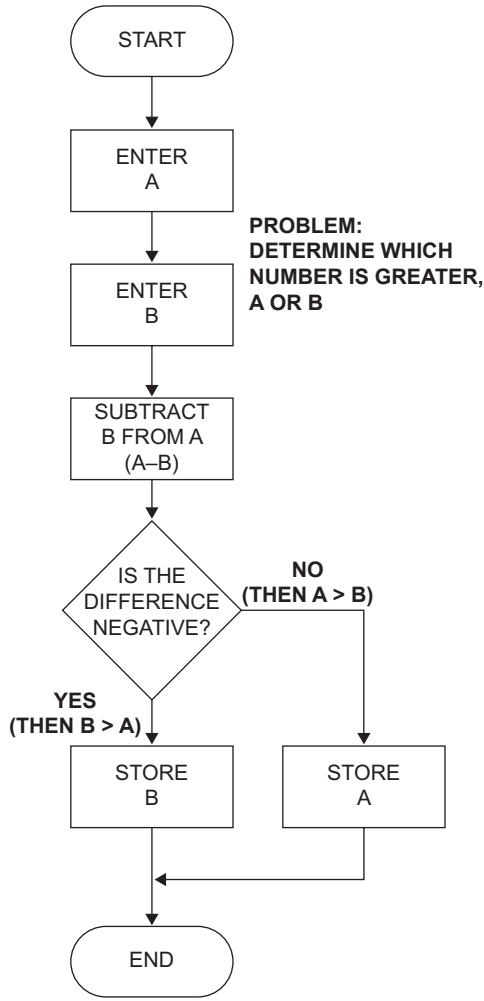


FIGURE 13.2 A flowchart illustrating a computer program.

problem into smaller and smaller logical pieces. Each piece, or module, performs some distinct segment of the solution.

All of the modules are then linked by a hierarchical structure that shows their relationship. This structure looks like an organization chart for a company. An example is given in Fig. 13.3. The main solution is divided up into three major modules. These modules are then divided into submodules that implement the primary module with smaller stand-alone programs. These submodules may then be further subdivided into even smaller logical segments. Some modules may be subroutines that may be used several times or called by any of the other modules or submodules.

Another feature of structured programming is to minimize or, if possible, completely eliminate unconditional branch operations. An *unconditional branch* or *jump* is a command or instruction that changes the order of a program from its normal, logical step-by-step sequence to something that might not be obvious. A common unconditional branch is the GOTO instruction. The tendency is to end one module with a GOTO so that the program branches to a submodule or some other logical segment of code. If too many GOTOs are used, the result is what is normally called spaghetti code. The result is a tangle sequence that is hard to follow in debugging or in maintaining the program.

The benefit of structured programming is that by dividing the program into smaller logical segments, it is easier to code, test, debug, and maintain. Also,

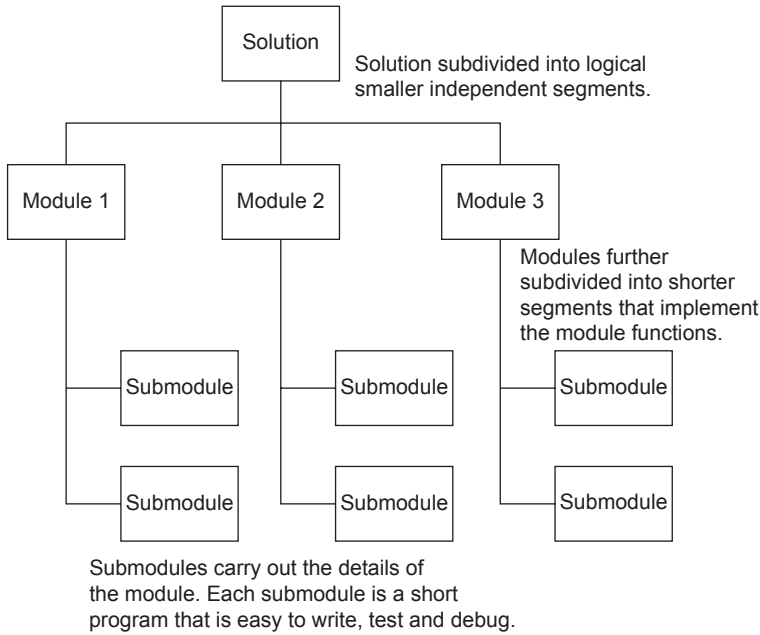

Solution
Solution subdivided into logical smaller independent segments.
Module 1
Module 2
Module 3
Modules further subdivided into shorter segments that implement the module functions.
Submodule
Submodule
Submodule
Submodule
Submodule
Submodule
Submodules carry out the details of the module. Each submodule is a short program that is easy to write, test and debug.

FIGURE 13.3 Structured programming divides a problem into smaller and smaller submodules.

it is easier to work with a smaller program when devising a solution. So if you take the time to do the partitioning up front when designing the program, the actual development time will be shorter, and chances are that the program will work right the first time.

The next step in the programming process is *coding*. This is the process of converting your solution, algorithm, or flowchart into an actual computer program. Here you take the instructions, expressions, or statements of the language you are using and write them in a sequence that implements your algorithm.

A common procedure with many programmers is to first code the solution in pseudocode. *Pseudocode* is a hypothetical or made-up language that is some hybrid of an English language statement of the operation and the actual instruction, statement, or command of the programming language. It enables the programmer to write the sequence of operations on paper first before actually using the language itself. Often the pseudocode can be written from the flowchart. This procedure helps you better see the logic of the procedure before committing to the final program code.

Programming involves much more than just the coding process, which most people associate with the term. Actually, coding usually takes roughly 20% or less of the total time involved in programming. Studies have shown that 40% of a programmer's time is usually devoted to problem definition, structure design, and the development or identification of an algorithm.

Most programmers agree that coding is actually the easiest part of programming. Once you become familiar with the characteristics and syntax of the language of use, and some basic programming tricks, coding becomes fast and easy. The use of subroutines greatly shortens and simplifies the coding process. On the other hand, defining the problem and developing a workable solution is much more difficult.

Once the coding is complete, you will enter the program into the MCU and test it. You enter the program with the editor to create your source code. The computer will then assemble or compile your program into machine code. In either case, the result is the binary object code stored in memory. At this point you are ready for the next programming step, testing and debugging.

Testing involves verifying that your program works. You will want to thoroughly test it to be sure that it does what it is supposed to do. Invariably, most programs do not work properly the first time. You may have made logical errors in sequencing, or perhaps you made errors in entering the code. If you used structured programming, you can test each submodule or subroutine by itself before linking together all of the various modules to perform the total operation.

Whatever the problems are, testing leads to *debugging*. Debugging is the process of working with the computer program and attempting to find errors and glitches. Most languages and program development software have built-in features that facilitate the debugging process. Once all the errors have been found and corrected, the program is ready to use.

The final step in the programming process is called *documentation*. This is an often-neglected but extremely important part of programming. Once the program is written and debugged, it is ready to use. The temptation then is to put the program into use and drop the project. However, it is extremely important that you document the program. Your problem definitions and solution work should be written up and filed away. Any charts, graphs, drawings, flowcharts, and other materials that you developed should be saved. All program listings should also be retained. In fact, it is desirable to prepare a detailed, written statement explaining the algorithm and the procedures involved. This is important for program maintenance, because it may be necessary to change the program at a later date. You may wish to add a feature or correct some part of the program to accommodate new conditions. It is easy to forget what you did months or years earlier. Also the original programmer may no longer be involved with the program. If a new programmer becomes responsible for changing a program, complete documentation is invaluable. Changing a program written by someone else is extremely difficult and, in some cases, virtually impossible without documentation.

The major investment in any programming project is programmer's time. A significant amount of time is usually required to develop a useful piece of software, which is why software is so expensive. In fact, the hardware is the least expensive part of the system in most embedded controllers.

One final word: Some programs may have to be changed over time. As the problem evolves, grows, or changes, the solution will have to be altered to meet current needs. New issues must be faced, or features may need to be improved to save time. In the case of a software product, improvements may have to be made to fix user-discovered bugs, improve performance, or keep the software competitive in the marketplace. It may be necessary to port the software to another MCU or OS.

All of these conditions fall into the category of maintenance. In fact, more time is spent on maintenance than in creating the original software. And, as indicated earlier, the better the documentation the faster and easier the maintenance can be carried out.

Developing Software for Embedded Controllers

The programming process just described applies to any microcomputer, be it a general-purpose personal computer or an embedded microcontroller. However, the procedure is somewhat different if you are developing programs for MCUs that are to be built into other equipment. Fig. 13.4 shows a block diagram of the complete microcontroller software development process.

A typical arrangement is to install the appropriate IDE on a PC. The PC then connects via a USB port to a development or evaluation board containing the target MCU. Next, once you have written your program in the programming language with the text editor, the assembler or compiler is called on to translate

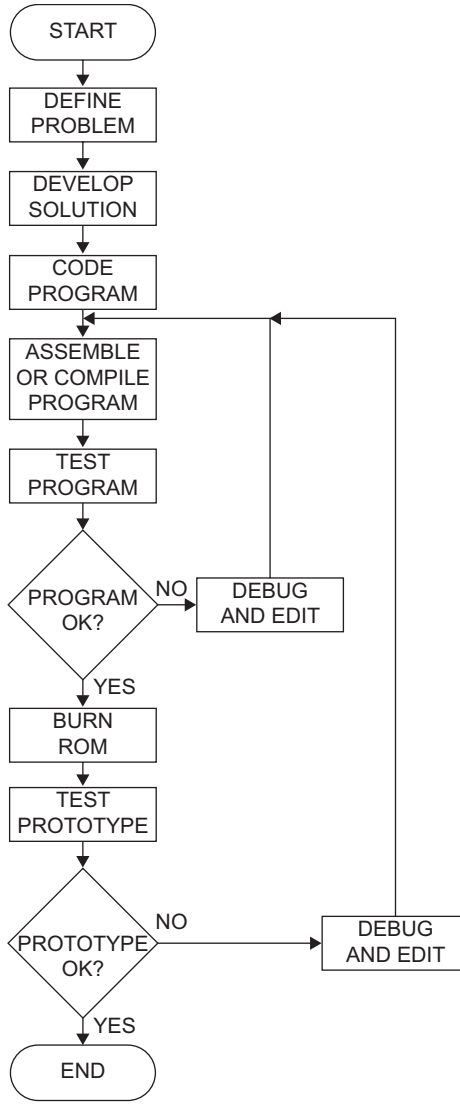


FIGURE 13.4 Block diagram of the complete microcontroller software development process.

that program into the machine code for the target microprocessor. All this is done on the PC.

Once the program has been written and the machine code generated, you test the program. The personal computer is not capable of executing the microprocessor instruction codes directly. However, an emulator program is usually available in the IDE that will allow the personal computer to test the program. An *emulator program* is a system-level program that duplicates the execution

of the MCU instructions on the personal computer. The emulator mimics the microprocessor so that the object code developed under the assembler or compiler can be tested. This allows the programmer to do any initial debugging. The problem with this procedure, however, is that the emulator sometimes does not operate in real time. It will not precisely duplicate the machine-cycle instruction execution rates of the microprocessor. The program will not be executed in exactly the same time frame as with the microprocessor. If time-related functions are important, the program should be thoroughly tested on a prototype of the MCU before being finalized.

Most development software includes a debugger, a program that helps to identify and isolate coding errors, logical errors, and other problems. The next step is to download the program to the MCU. This is usually done by way of a USB cable that connects the PC to the MCU development board or a prototype of the product being developed. Functional testing can then take place. The program is downloaded to the development board and stored in a ROM or flash memory. Thus the microprocessor becomes dedicated to a specific application. Then additional testing can be performed. The program in a ROM is typically referred to as *firmware*, that is, software that exists in an electronic component.

Microcontroller Unit Interfacing

In addition to programming an MCU for a specific task, you also need to interface the MCU to the external devices that make up the device you are designing. Such peripherals are sensors such as light or temperature sensors or controlled devices such as LEDs, relays, or motors. Usually some form of circuit or device is needed between the MCU input/output lines and the peripheral devices.

Outputs. The I/O lines of the MCU input or output standard binary voltage levels. These are typically in the 1.8–5 V range for a binary 1 and 0 to a few tenths of a volt for a binary 0. Depending on the MCU and supply voltage, the output lines can usually sink or source current in the 15–40 mA range. As a result, the output line can operate low-power devices such as LEDs directly

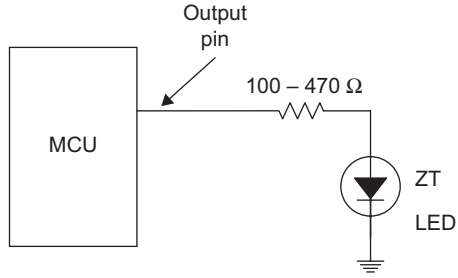


FIGURE 13.5 Driving an LED directly from the MCU output.

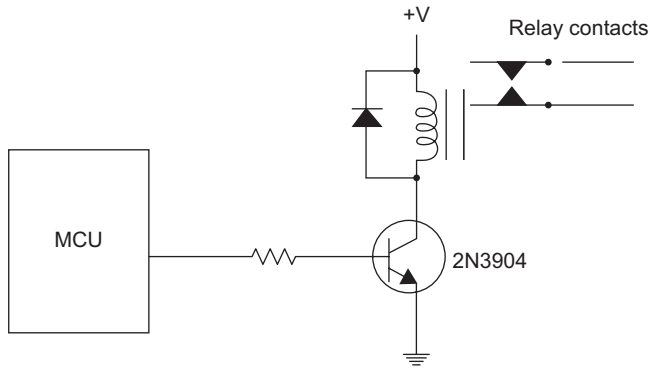


FIGURE 13.6 An NPN driver transistor for higher loads.

without an interface. Fig. 13.5 is a simple example. The resistor limits and sets the current level.

For higher current/voltage devices an interface transistor is usually needed. Fig. 13.6 shows an NPN transistor driving a relay coil. The coil may be operated by the same power supply as the MCU or a higher voltage. The diode protects the transistor from the inductive spike caused by the inductive coil being deenergized. This simple interface can also control a solenoid.

Fig. 13.7 shows a MOSFET operating a motor. A protective diode is usually built into the transistor. If bidirectional control of the motor is needed, the H-bridge circuit discussed in Chapter 12 (Figure 12.20) can be used.

A useful output is pulse width modulation (PWM). A PWM output from an MCU is a continuous DC rectangular wave whose duty cycle can be varied by the program. Some devices or circuits take this signal and average it into a continuous DC voltage. Varying the duty cycle causes the DC average to vary. (See Duty Cycle and PWM and Figure 4.22 in Chapter 4). The duty cycle is selected in the program usually by setting a numerical value. The duty cycle can also be changed by the program. Two example applications are varying the brightness of an LED and controlling the speed of a DC motor.

Inputs. A common input is a switch or pushbutton. The idea is to connect the switch into a circuit that generates a binary 0 or 1. A typical circuit is shown in Fig. 13.8A. The single-pole single-throw (SPST) switch is normally open. The pull-up resistor keeps the MCU input at +5 V. When the button is pressed, the switch contacts close grounding the resistor and producing a zero input. Instructions in the program read the status of the input line. Some action is initiated if the input goes low.

An alternate arrangement is shown in Fig. 13.8B. The resistor keeps the MCU input low or ground and binary 0 level. When the pushbutton is depressed, +5 V is applied to the input. Again the MCU tests the input with an instruction to see if it is binary 1. If it is, some other action will occur.

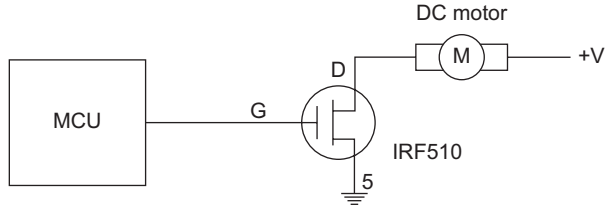


FIGURE 13.7 An N-channel enhancement mode MOSFET driving a DC motor.

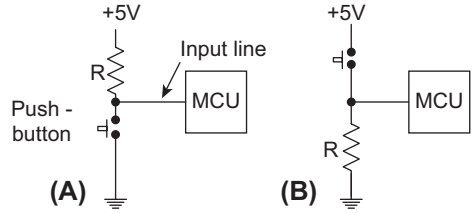


FIGURE 13.8 Using a pushbutton switch to generate an input logic level.

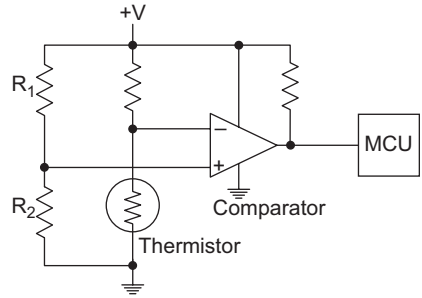


FIGURE 13.9 A comparator and thermistor used for temperature sensing.

A comparator can also be used for an interface. Fig. 13.9 shows a thermistor temperature sensor as the input to the comparator. Voltage divider R_1-R_2 sets the temperature level. As the temperature increases, the thermistor resistance decreases when the voltage from the thermistor divider changes the comparator input and switching the output from a 0 to 1 or vice versa. This signal is applied to an MCU input that is read by the program to determine if the temperature is above or below the level set by the pot. Other resistive sensors such as a photoresistive light sensor can be used for a similar function.

Some devices may require the use of an analog-to-digital converter (ADC). Some sensors or sensor circuits such as a voltage divider or bridge output a DC voltage proportional to the analog quantity being sensed. The ADC translates this voltage into an equivalent binary value that is sent to the

MCU. As it turns out, most MCUs have one or more internal ADCs so no interfacing is needed other than conditioning the analog signal for application to the MCU input.

PLATFORMS FOR LEARNING PROGRAMMING

The best way to learn programming is to start doing it. You will probably need to read some books, participate in online tutorials, or take a formal course. Whatever your approach to teach yourself programming, you will need a platform for learning. The platform, for lack of a better term, is a mix of hardware and software that is organized for learning. Many of these platforms are available for different languages and MCUs. I have reviewed several of these, and described here are the four that I can recommend. They teach either BASIC or C. For complete beginners I recommend those teaching BASIC. If you plan to use C in your work or just want to challenge yourself, select a C platform.

Parallax BASIC Stamp 2

The BASIC Stamp 2 is a complete microcontroller module that uses a Microchip Technology PIC MCU with RAM and flash memory on-chip in addition to inputs and outputs including a USB port for connecting to a PC for programming. It is designed to be built into other equipment or projects. The Stamp 2 is programmed in the PBASIC language. The Parallax Stamp has been around for about 17 years, so it is highly developed and widely used in education to teach programming.

The Stamp 2 is available in a wide range of forms from simple plug-in modules to complete learning kits that include a breadboarding socket, multiple components, and comprehensive project manuals. A free IDE is available for download from the Parallax site. I reviewed the BASIC Stamp Activity Kit that comes with the breadboard and parts. See Fig. 13.10. The manual is a self-teaching guide that instructs you in the BASIC language and electronic interfacing. The kit is a complete package of all the things you need to start learning programming. I recommend it.

PICAXE

PICAXE is another platform that uses a Microchip Technology PIC MCU and is programmed in BASIC. The package is essentially a version of the PIC MCU family in a DIP IC that can be plugged into a breadboarding socket. It has been preprogrammed with firmware that allows the MCU to be programmed by way of IDE software on a PC. Connection is by way of a USB port on the PC. You can then add other interfaces such as sensors or controlled devices as your project dictates. The BASIC language is easy to learn and use. The IDE is a

FIGURE 13.10 The Parallax BASIC Stamp Activity Kit experimental board is designed to be operated from a 9-V battery. The PIC MCU is the IC above the reset button in the center.

free download, and there is plenty of support, help, and instruction on the companion website. This is a low cost way to build projects with a microcontroller.

Arduino

The Arduino is a wildly popular microcontroller module that uses an Atmel (now part of Microchip Technology) MCU. The module provides a USB port for connection to a host PC for programming and access to multiple input and output lines. It is programmed in a version of the C language. A free IDE is available for download.

The Arduino has been around for several years now, and multiple versions are available. Dozens of different products are offered by multiple companies. You choose the MCU type depending on your need for memory sizes, interfaces, and I/O ports. My recommendation is to select the simplest form called the Arduino Uno R3. It uses an 8-bit MCU called the Atmel ATmega328P. The Uno is powered by the USB port or an external 5 V supply. A free online IDE is available. Using the C language variant provided, you write code to develop a program called a "sketch."

The C language is more daunting to learn than BASIC, but it offers far more power and capability than BASIC. If you want to create more complex projects as a maker or begin to use C in your career, then C is the better choice. The Arduino is probably the best learning platform as there is a large quantity of information available to help you including books, tutorials, and products. One popular type of accessory is the "shield," a small PCB that plugs into the connectors on the Arduino board. The shields are various forms of interfaces and I/O devices such as wireless, motor control, GPS, and many others.

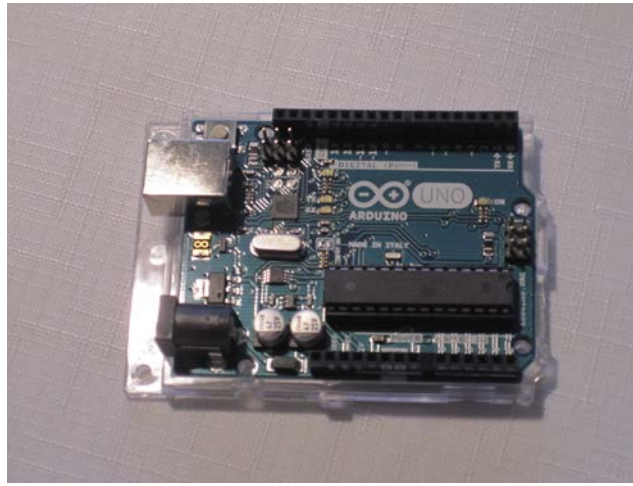


FIGURE 13.11 The Arduino Uno R3 is one of the most widely used microcontroller learning platforms.

I evaluated the Arduino by using supplier SparkFun's Inventors's Kit. See Fig. 13.11. It contains the Uno, a breadboarding socket and a batch of parts to use in interfacing and building external circuits. An instruction manual leads you through projects that demonstrate interfacing and C coding, a good choice for the beginning programmer.

LaunchPad

The LaunchPad is one of the Texas Instruments' development kits for the MPS430 series of MCUs. It comes as a PCB module with the MPS430FR6989 16-bit MCU that features 128 KB of FRAM. Refer to Fig. 13.12. The board also includes some LEDs, pushbuttons, an LCD readout, and other components to use in demonstration projects. A USB port connects the LaunchPad to the PC. Free IDEs are available for download. This is a very serious professional platform for those committed to learning C. No companion instructions are provided but many manuals and tutorials are available online. I acquired the LaunchPad as part of an online college course from Udemy that teaches C with lab projects.

Advanced Alternatives

If you are really adventuresome, you may want to select a more advanced platform. One of the most popular is the Raspberry Pi 2 or the newer more powerful Raspberry Pi 3. Both use a version of the popular ARM type processor, a powerful 32-bit microprocessor. It comes in the form of a development board with memory, I/O, and other resources. The Raspberry Pi uses variations of the Linux OS. IDEs

FIGURE 13.12 The Texas Instruments' LaunchPad development board uses an MPS430 microcontroller.

supporting different programming languages are available. Prices are very reasonable. I do not recommend these for beginners, but they can be the next step up after you have mastered programming.

Another interesting advanced option is Parallax's Propeller. This platform uses Parallax's own MCU chip called the P8X32A. It features eight (yes, eight) MPU cores along with memory and I/O. You program it in C, assembler, or a companion language called Spin. Once you have mastered BASIC on your Stamp platform and need more compute power, this may be a good next step for you.

LEARNING PROGRAMMING

There is not enough space in this book to teach a programming language. But you can learn it on your own. If you are not sure about self-learning, you could find a local college or university that offers continuing education courses for adults. Otherwise, give the self-learning idea a try. Here are some suggestions.

Books

There are literally dozens of books covering C programming. Not so many on BASIC. Some books are more specific to teaching the Arduino version of C. I reviewed several, but I can recommend two that may be helpful to you.

- *C Programming With Arduino*, by Warwick A. Smith, Elektor, 2016.
- *Arduino for Dummies,* by John Nussey, John Wiley & Sons, 2013.

I suggest that you go to your bookstore and see what is on hand. Your local library may have some. Alternately, do an Internet search on the Amazon

and Barnes & Noble websites to see what is available. I recommend that you invest in at least two or three books as when one is not clear and helpful the others may be.

Learn by Example

Most of the books provide example programs. Kits such as the SparkFun (Arduino) Inventor's Kit and the Parallax BASIC Stamp Activity Kit provide hands-on experiments and projects with typical programs. Initially no programming is necessary. You simply enter the programs and run them. By implementing enough of the programs and analyzing them in detail, you can learn how to program on your own. In fact, with enough examples, you can put together several programs and modify them to fit your needs. If you are just learning programming, I highly recommend one of the experimenter's kits as a great starting point.

Online Tutorials

If you do an Internet search for programming tutorials, you will be surprised at how many there are for both BASIC and C. Some are free and others have a fee associated with them. Some are video based (such as YouTube), others are PDF documents, and some have presentations. Take your pick. Take one to start and then do another just to firm up your knowledge.

Online College Courses

Many colleges and universities now offer online college-level courses in a wide range of subjects. Such programs are referred to a Massive Open Online Courses or MOOCs. Programming is one popular topic. Many are free and others have small fees. If you are interested in a more formal course at the college level, from major institutions, take a look. Go to the websites of Coursera, edX, and Udemy, and search for a C or BASIC course. I selected a course called *Microcontrollers and the C Programming Language* from Udemy. It is taught online by Professor Mark Budnik of Valparaiso University in Indiana. It includes lab programming and interfacing projects using the Texas Instruments' LaunchPad described earlier. The course was offered at very low cost, but the LanuchPad was a minor added expense. A very challenging and time-consuming course but it does the job. There are others you can identify online.

Apply What You Learn

Reading relevant books and taking courses are good ways to get started, but they will not make you a programmer. To learn programming, you must do programming. You must write code, screw up, and retry. You must test the process yourself, failing along the way, and adjusting. This is still the best way to learn

programming. Start with small programs and then progress to more complex applications as you improve your knowledge and skill. The projects outlined next will get you started.

Project 13.1

Select a Learning Platform and Language

If you have not already done so, choose your language and acquire one of the platforms or its equivalent described earlier. The complete kits cost a bit more but will get you started faster and easier than just investing in a development board. See Appendix B for sources. You should be able to get started for about $100. It is a good investment.

An interesting exercise is to investigate the programming languages to find out which ones are the most widely used. As a challenge in this project, perform an Internet search to discover the top three most popular programming languages.

A Word About the Following Projects

The projects that follow are intended as demonstrations that show what is possible and how to do it. If you invest in a microcontroller, you can try out these projects. You can just copy the programs into the IDE editor and test them out. The programs are instructive in showing you the programming process. However, you will need further learning before you become a programmer. Your goal should be further study as outlined earlier. Practice makes you more knowledgeable as you try, fail, and then try again and succeed.

Project 13.2

Blink an LED

One of the simplest applications is to flash an LED off and on. You first connect a resistor and LED to one of the output pins on your development board as shown in Fig. 13.5. Some boards such as the Arduino Uno R3 and the TI LaunchPad have this LED already connected on the PCB. As for the code, it is simple. Earlier in this chapter you saw the BASIC code to do this. Here is the code for the BASIC Stamp 2. Wire the LED as shown in Fig. 13.5 using a 470-Ω resistor on pin 7.

```
' {$STAMP BS2}
' {$PBASIC 2.5}
DO
    HIGH 7
    PAUSE 500
    LOW 7
    PAUSE 500
LOOP
```

The first two lines of code that begin with an apostrophe set up the programming software in the Stamp IDE. The remaining code flashes the LED as explained earlier in the chapter.

Project 13.2—cont'd

Below is a listing for the C code to flash the LED. Wire the LED as in Fig. 13.5 to pin 9. Use a 470-Ω resistor. If you are using the Arduino Uno, you can use the onboard LED already connected to output pin 13. Just substitute 13 for 9 in the code below.

```
int ledPin = 9;
void setup()  {
pinMode(ledPin, OUTPUT); }
void loop()  {
      digitalwrite(ledPin, HIGH);
      delay(500);
      digitalwrite(ledPin, LOW);
      delay(500);
}
```

The first line tells the Arduino to assign the variable ledPin to the integer value of 9. The LED and resistor would be connected to pin 9. Next the void setup() command tells the processor to execute the code between the two following curly brackets. The pinMode command tells the processor that pin 9 is an output port. Now the void loop() tells the processor to set up a loop to run the code between the following curly brackets. The digitalwrite command tells the processor to set pin 9 to the high or binary 1 state turning on the LED. The delay command then causes a pause of 500 ms or one half second. Next the digitalwrite command tells the processor to set pin 9 to low or binary 0 turning off the LED. Another delay or pause of 500 ms occurs. Note all command lines have to end in a semicolon. The program then loops back to repeat.

Project 13.3

Use a Pushbutton Switch for Control

This project will illustrate how to apply an input to the microcontroller. The pushbutton is a common input device. The basic interface is like that shown in Fig. 13.8. The micro looks at the input pin and senses the state. If it reads the right condition, it will cause something to happen. In the example to follow, the goal is to flash the LED five times when the pushbutton in depressed. The code in both BASIC and C are outlined below.

Here is the code for BASIC Stamp 2. It uses the same flash code in the previous BASIC example but is modified by to flash five times and then stop. The pushbutton should be wired like that in Fig. 13.8B on pin 5.

```
' {$STAMP BS2}
' {$PBASIC 2.5}
counter VAR Byte
FOR counter = 1 TO 5
DO
      IF (IN5 = 1) THEN
      HIGH 7
```

Continued

Project 13.3—cont'd

```
        PAUSE 500
        LOW 7
        PAUSE 500
    NEXT
    LOOP
```

The first two lines beginning with the apostrophe sets up the programming software and must be included. The next line sets up a variable called counter that can be up to a byte long. The DO instruction sets up loop to repeat the program. The IF…THEN line sets up another inside loop that reads input pin 5 to determine its state. It will look at the pin ten times per second. If input pin 5 goes high or 1, it signals the program to execute the code flashing the LED. The program then flashes the LED five times as the loop NEXT command counts the number of flashes and then stops. The LOOP instruction sets up the loop again as the program waits until the button is pressed again. The program is a loop within a loop where the inner loop is conditioned by the number of repeated flashes. The outer loop is conditioned by the state of the pushbutton.

The C code for the Arduino to initiate the five LED flashes is shown below. The pushbutton should be wired as shown in Fig. 13.8A using a 10k-Ω resistor. The code is set up to use pin 2 as the input. Pin 9 is used as an output for the LED as in the previous code.

```
int ledPin = 9;
int inputP = 2;
int val = 0;
void setup()   {
pinMode(ledPin, OUTPUT);
pinMode(inputPin, INPUT);
}
void loop()   {
      val= digitalRead(inputPin);
      if (val == HIGH) {
      digitalwrite(ledPin, LOW);
      } else {for (int i = 0; i < 5; 1++) }
      digitalwrite(ledPin, HIGH);
      delay(500);
      digitalwrite(ledPin, LOW);
      delay(500);
}
```

The program sets up pin 9 as the output for the LED and pin 2 as the input. The void loop() sets up a loop to repeat the flashing five times. The program reads the state of the input pin with the digitalRead statement. If it is HIGH, the button has not been pressed to close the circuit. The "if" statement evaluates the input, and if it is HIGH, it turns off the LED with a digitalwrite command. However, if the input goes LOW, the "else" statement initiates the flash sequence. The "for" statement counts the number or flashes and then terminates the program.

Chapter 14

Soldering

An Essential Skill for Electronics

In this Chapter:

- The importance of soldering.
- What is solder?
- Soldering tools.
- How to solder.
- How to desolder.
- Projects.

INTRODUCTION

Soldering is the process of melting a metal alloy called solder for the purpose of joining together two or more other metals. The solder, when melted, becomes a liquid and flows over the other metals to be joined. When the solder cools, it hardens and adheres to the other metals creating a strong mechanical bond as well as a highly conductive connection. Most interconnections of electronic parts and printed circuit boards (PCBs) are made with solder. For that reason, soldering is an important skill for any electronic engineer, technician, hobbyist, experimenter, maker, or other do-it-yourselfer. This chapter shows fundamentals of soldering and some projects to practice with and learn from.

What is Solder?

Solder is a soft metal alloy made up of tin and lead. The usual mix is 60% tin and 40% lead. Other mixes are available, but the 60/40 category is the most common in electronics work. Solder has a low melting point of about 360–370°F or in the 180–190°C range. It is usually melted with a handheld tool called a soldering iron. The solder is usually made in the form of a thin flexible wire. When melted, the solder becomes a liquid and easily flows over the other metals to be joined. The solder cools and hardens and adheres to the other metals making a solid joint.

Electronics Explained. http://dx.doi.org/10.1016/B978-0-12-811641-8.00014-X
Copyright © 2018 Elsevier Inc. All rights reserved.

Most wire solder contains a continuous core of a material called rosin flux. When heated, the flux melts with the solder and is used as a cleaning agent. The metals to be joined often oxidize and resist the solder. The flux clears away the oxidation and other surface obstacles to allow the solder to adhere to the metals. Some types of solder used in mechanical work use an acid core flux. This is deadly to electronic parts. Never use it. Use rosin core solder only.

Solder containing lead has been ruled undesirable in some applications. Yet it is still the best solder. It will not harm you. You can also get solder without lead. Such solder is mostly tin with a small amount of silver or copper or both. The melting point is typically 5%–10% higher so extreme care should be taken when soldering delicate temperature-sensitive electronic parts.

Soldering Tools

The main tool of soldering is the soldering iron. See Fig. 14.1. It has an insulated handle, a heating element with an AC power line cord and plug. The heating element heats a metal tip that actually does the soldering. The tips come in many sizes but a small tip is best for use on modern components.

Soldering irons are rated by the power they consume and heat they dispense. Ratings run from about 15 W to over 100 W. For electronics work an iron with a rating of 25–35 W is best. It is hot enough to do the soldering but will not do heat damage to sensitive electronic components. Be sure that the soldering iron has a small narrow or pointed tip to accommodate most small electronic component leads.

A helpful accessory is a soldering iron stand or holder to keep the iron from burning the bench or table you are using. Also useful is a wet sponge. It is used

FIGURE 14.1 A common soldering iron used in electronic work.

FIGURE 14.2 Tools used in soldering. On the left is a wire stripper. Next is a pair of needle-nose pliers. On the right is a side cutter for wire.

to keep the soldering tip clean. A sponge holder is often part of the soldering stand.

Other useful soldering tools are illustrated in Fig. 14.2. The wire stripper helps remove the insulating cover from wires to be soldered. It cleanly cuts off the insulation without damaging the copper wire. This is a must tool and a mandatory substitution for a knife that can nick the wire while stripping the insulation.

A pair of needle-nose pliers is sometimes helpful in bending or holding component leads or wires. The side cutters are used to cut wires or trim away component leads or wires after soldering. All of these tools speed up and simplify your soldering work and are a good investment.

If you are going to work with tiny surface mount parts, you should have a pair of tweezers to handle them or to hold them in place as you solder. A magnifying glass is also a useful accessory when using tiny parts.

Soldering Procedures

The most common soldering scenarios are soldering wires together or soldering electronic parts to a PCB. Fig. 14.3 shows the first case. When connecting two wires, you first remove any insulation first. You will need an inch or more of bare wire to make the connection. Then make a good physical connection by wrapping one wire around the other as shown. Then touch the clean tip of the iron to the connection. Let the connection heat for a few seconds, then apply the solder. The secret to a good connection is to apply the solder to the heated wires and not to the iron tip. Let the solder flow over the wires until coated. Do not use

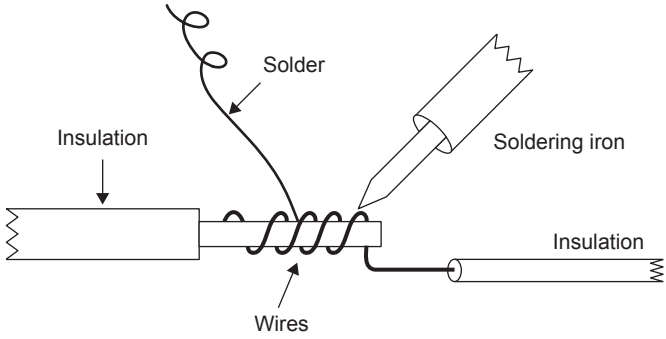


FIGURE 14.3 Soldering two wires together. Apply solder to the heated wires not to the iron tip.

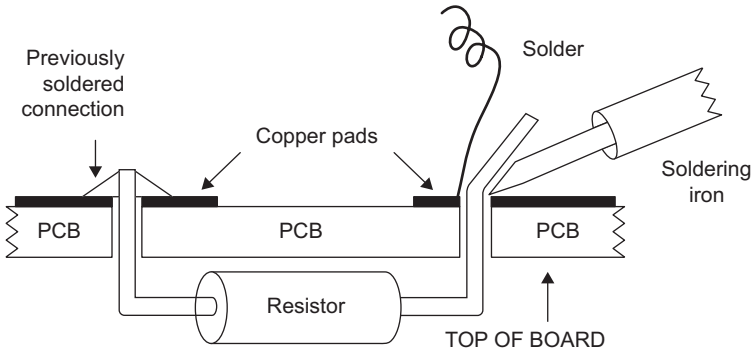


FIGURE 14.4 Soldering components to a printed circuit board.

too much solder. Once the solder flows over the wires, remove the iron and let the connection cool. It should look shiny and bright, not dull gray.

Another common soldering situation is connecting components to a PCB. See Fig. 14.4. This shows a resistor lead being soldered to a copper pad on the PCB. The resistor lead is usually inserted into a hole on the board and is then soldered to a copper pad or area on the bottom of the board.

The procedure is to bend the lead and insert it into the hole. The resistor will lay flat on the board as shown. Bend the lead over to hold it in place, then solder. As with soldering wires, or anything for that matter, apply the heat to the copper pad and resistor lead for a few seconds. Then flow the solder over the connection. Do not apply the solder to the iron tip. And do not let the lead or the board move as you solder. Use minimum amount of solder to cover the connection and not more.

Remove the iron and let the connection cool. No movement should occur during the cooling process, or it will produce what is called a “cold” solder joint. Instead of looking bright and shiny the connection will look crumbly and dull gray. Movement during cooling is the most common cause of cold

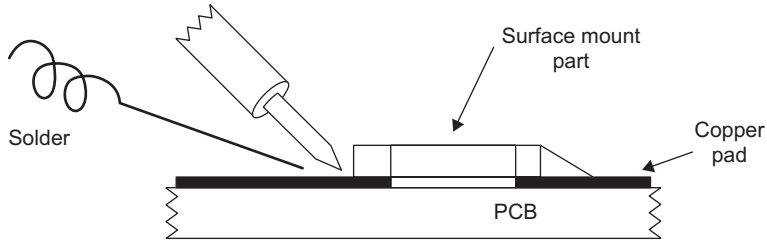


FIGURE 14.5 Soldering a surface mount part to a PCB.

joints. A cold joint does not make a good electrical connection. If this occurs, simply reheat the joint and then let it cool without movement. Do not add more solder.

Fig. 14.5 shows another soldering situation. Here a surface mount part is placed on the top of the PCB and is soldered to a copper pad. No hole is used or needed. Surface-mount parts are tiny and hard to work with. Hold the part carefully in place, then heat the junction of the part and the copper pad. Use a small iron tip to avoid accidentally touching adjacent pads or parts. Then flow the solder over the joint. Use as little solder as possible. Be very careful not to move anything as the solder cools.

There are a couple of precautions to observe. First, use as little heat as possible. Most PCBs are sensitive to heat and with too much heat you can cause the copper pad on the PCB to peel free and possibly break off. This is a serious problem that is often catastrophic for an expensive electronic PCB. Too much heat can sometimes damage a component such as an integrated circuit or resistor. The correct balance is to use just enough heat to melt the solder but not enough to damage anything. A few seconds is all you usually need.

Second, be careful of cold solder joints. Do not move anything as the solder cools. A cold joint will also result with not enough heat. The giveaway is a dull or rough-looking joint rather one that is smooth and shiny. Cold solder joints usually do not create a conductive path between the copper pad and the component. An open circuit is the result.

Third, most connections on a PCB are very close together. Spacings between components and IC pins of 0.1 in. (2.54 mm) or less are common. While you are soldering one connection, be careful not to disturb an adjacent connection. A common problem is using too much solder on a connection that slops over to a nearby connection causing a short or solder "bridge." To fix this, remove any excess solder from the connections to remove the bridge.

Desoldering

A related skill is desoldering. Desoldering is the process of disconnecting things that were previously soldered. It involves removing the solder first, then physically breaking the parts from one another. Desoldering is usually common when

FIGURE 14.6 Tools for desoldering, a solder sucker and solder wick.

repairing electronic equipment by replacing a defective part or when making and correcting a mistake.

The tools of desoldering are shown in Fig. 14.6. The first is a solder sucker. It is a simple vacuum pump that literally sucks the molten solder from a joint. You heat the joint to be disconnected, then simultaneously apply the solder sucker to remove the solder. You usually have to repeat the procedure several times to get the solder off. Once you remove as much solder as possible, you physically pry the parts apart with the tip of a knife or a pair of needle-nose pliers. Be careful not to pull the copper foil pad off the PCB.

An alternative or a companion to the solder sucker is solder braid or wick. This is a narrow flat braid of fine copper wires coated with flux or other chemical that attracts solder. You place the braid on the connection to be desoldered, then heat the braid with the iron. Once the solder melts, it wicks up into the braid. The braid absorbs the solder. As with the solder sucker, you usually have to apply it several times. Be sure to cut off the braid that has absorbed the solder. Always use fresh piece of braid. Again, do not use too much heat and damage the PCB or part.

Projects

The best way to learn soldering is to solder. It is a manual skill that takes a bit of practice. It is not difficult but you do need to try it out first, then practice it several times. The following projects will help.

Project 14.1

Acquire the Tools

If you are planning to do serious electronic work, you need the right tools. The first step is to go get the tools described above. You may be able to get them individually at a DIY store such as Lowe's or Home Depot. RadioShack or Fry's should have them. Online catalog sources, such as All Electronics, Jameco, or others, have them. Some vendors offer complete packages of all the tools in one kit. This complete kit is the best approach if you have no tools now.

Project 14.2

Solder Two Wires

A common need is to connect two wires. An example you may have experienced is the problem of not being able to plug stranded wire into a breadboarding socket. The 9-V battery connector you may have used has stranded wires that are not stiff enough to plug into the breadboard. One way to fix this problem is to attach some short solid hookup wire leads to the battery clip wires. The hookup wires will plug right into the socket.

Here is the procedure:

- Cut two lengths of #22 gauge hookup wire several inches long.
- Use the wire strippers to remove about one half inch (1.25 cm) of insulation from each end of the wires.
- Also strip about one half inch of insulation from each battery clip wire.
- Then wrap the stranded battery clip wire around the solid hookup wire as previously shown in Fig. 14.3.
- Solder the connection by heating the wires first, then flowing solder over them. Do not apply the solder to the soldering iron tip. Also use a minimal amount of solder. Let the connection cool.
- Repeat the procedure for the other battery clip wire.

Project 14.3

Build a Kit

The best way to practice soldering is to build a kit. This was recommended earlier in Project 4.1. If you have not built a kit yet, now is a good time to do so. I recommend the solder practice kit (SP-1A) where you build a siren with flashing LEDs. The kit also provides an area on the PCB to practice soldering skills. You can get this kit from Elenco (www.elenco.com) or Jameco (www.jameco.com).

Any other small low-cost kit such as a power supply will also provide plenty of soldering experience. Refer back to Project 4.1.

This page intentionally left blank

Appendix A

Book References

Here is a list of books for those who wish to dig deeper. You will find lots of basic electronics books out there, but these are my favorites as well as some of my own.

American Radio Relay League. *The ARRL Handbook for Radio Communications*; 2017. The focus is on wireless but the book also has excellent coverage of electronic fundamentals.

Ashby D. *Electrical engineering 101*. Newnes/Elsevier; 2008. A good basic book that delves more into the circuits than this book. A good next step from here.

Frenzel LE. *Crash course in electronics technology*. 2nd ed. Newnes/Elsevier; 1996. Out of print now but still available in the used market. A programmed introduction to electronics.

Frenzel LE. *Crash course in digital technology*. 2nd ed. Newnes/Elsevier; 1998. Out of print now but still available in the used market. A programmed introduction to digital circuits. Getting a bit dated now but still valid.

Frenzel LE. *Crash course in PC and microcontroller technology*. Newnes/Elsevier; 1999. Out of print now but still available in the used market. A programmed introduction to micros. Getting dated but the fundamentals are still good.

Frenzel LE. *Principles of electronic communications systems*. 4th ed. McGraw-Hill; 2016. Recently updated and it takes the systems approach to the subject. A college text but very readable.

Frenzel LE. *Contemporary Electronics: Fundamentals, Devices and Circuits, and Systems*, McGraw Hill, 2014. A college textbook covering DC, AC, semiconductors, and linear circuits with a systems emphasis.

Horowitz P, Hill W. *The art of electronics*. 3rd ed. Cambridge University Press; 2015. Recently updated, a good example of how to present electronics. A great reference. A lab manual is also available.

Kuphaldt, TR. *Lessons in electric circuits*. Self-published; 2000–2009. A complete electronics book online and free for download. It covers DC and AC circuits, semiconductors and basic circuits, and digital. A lab manual is available. Go to www.openbookproject.new/electricCircuits.

Maxfield C. *Bebop to the Boolean Boogie*. 3rd ed. Newnes/Elsevier; 2009. First published in 1995, it was a hit. A great introduction to digital practice and circuits.

This page intentionally left blank

Appendix B

Projects Parts List

PARTS SOURCES

These are recommended but there are others.

Adafruit: www.adafruit.com
All Electronics: www.allelectronics.com
Digi-Key: www.digikey.com
Jameco: www.jameco.com
Marlin P. Jones & Associates: www.mpja.com
Mouser: www.mouser.com
SparkFun: www.sparkfun.com

CHAPTER 2

Digital multimeter (DMM). Must measure DC and AC voltages, DC current, and resistance. More expensive models may measure capacitance and test transistors, but these are not necessary for the projects in this book.

CHAPTER 3

- Batteries, four AA cells or a 9V battery
- Battery holder for AA cells (Get one with preconnected cells and an off/on switch. Jameco 216187 is recommended. In fact, buy two as you will need another supply for later projects.)
- Battery clip for 9-V battery (Buy two as you will need another supply later.)
- Breadboarding socket (Buy the larger one for more complex circuits. Two is recommended.)
- #22 solid copper hook up wire, insulated (At least several feet for future uses.)
- LED, any generic type or color
- 220-Ω ¼-W resistor
- 330-Ω ¼-W resistor
- 100k-Ω ¼-W resistor
- 100-µF electrolytic capacitor, voltage rating >10V

- MOSFET transistor IRF510, 2N7000, or equivalent
- Tools: soldering iron (25–35 W), rosin core solder, side cutters, wire strippers

Note: If you plan to do the projects in this book, you will need multiple values of resistors. Most parts vendors offer assortments of the most common value resistors with 5 or 10 of each value. This is a highly recommended purchase as it will save time and be more convenient.

CHAPTER 4

Project 4.1

Recommended kit is the dual adjustable regulated power supply from Jameco: Model JE215 (20626).

Project 4.2

Recommended VI packages:

- Digilent Analog Discovery or Analog Discovery 2 with Waveforms software
- National Instruments' my DAQ with LabVIEW software
- Velleman PCSU1000 oscilloscope or PCSGU250 oscilloscope with signal generator

Project 4.3

Possible power supply choices:

- Dual adjustable regulated power supply kit from Jameco: Model JE215 (20626)
- Batteries: Two each 4-AA cells in a holder (6V) or two 9-V batteries with clips
- Power supplies in VI units
- Wall adapter AC to DC power supplies, regulated preferred, 5V

Project 4.4

Parts for Fig. 4.26:

- AC to AC wall adapter transformer: 5V (Cut the connector off the cable and tin the wires with solder to plug into the breadboarding socket.)
- 1k-Ω potentiometer (Get the kind that plugs into the breadboarding socket.)

Parts for Fig. 4.27:

- 555 timer IC 8 pin dual inline package (DIP)
- 10k-Ω ¼-W resistors (3)
- 0.05-μF ceramic capacitor
- 0.1-μF ceramic capacitor
- 47-μF electrolytic or tantalum capacitor, voltage > 10V

Project 4.5

Parts for Fig. 4.31:

Same as for Fig. 4.27 but add:

- 100-Ω ¼-W resistor
- 2-in., 8-Ω speaker

Parts for Fig. 4.32:

Same as for Fig. 4.27 but add:

- 220-Ω ¼-W resistor
- LED

Project 4.7

Parts for Fig. 4.33:

Same as for Fig. 4.26 plus:

- 1N4001 silicon diode
- 1000-µF electrolytic capacitor, 16V or higher
- 0.33-µF capacitor
- 0.1-µF capacitor
- 1k-Ω, ¼-W resistor
- 7805 linear regulator, TO-220 package

Project 4.8

Parts for Fig. 4.35:

- TL081 op amp or equivalent (741, etc.)
- 15k-Ω, ¼-W resistor
- 4.7k-Ω, ¼-W resistor
- 1k-Ω pot

Parts for Fig. 4.36:

- TL081 op amp or equivalent (741, etc.)
- 6.8k-Ω, ¼-W resistor
- 1k-Ω, ¼-W resistor
- 1k-Ω pot
- Wall transformer

CHAPTER 5

Project 5.2

Parts for Fig. 5.31:

- 5V power supply as suggested in Project 5.11
- 74HC00 quad NAND gate IC
- 220-Ω, ¼-W resistor

Continued

Project 5.2—cont'd

- LED

Parts for Fig. 5.32:

- Same as parts for Fig. 4.32.
- Same as parts for Fig. 5.31.

Project 5.3

Parts for Fig. 5.33:

Same as parts for Fig. 4.32, plus:

- 74HC161 binary counter IC
- LEDs (4)
- 330-Ω, ¼-W resistors (4)
- 1k-Ω ¼-W resistors (4)
- 0.01-μF capacitor

CHAPTER 7

Project 7.6

Parts for Fig. 7.23:

- Two 6 or 9V supplies
- Part for 555 timer circuit same as for Fig. 4.32
- Radiometrix TX3A transmitter
- Radiometrix RX3A receiver
- 2N3904 NPN transistor
- 470-Ω, ¼-W resistor
- 10k-Ω, ¼-W resistor (2)
- 27k-Ω, ¼-W resistor
- LED

CHAPTER 12

Project 12.2

Parts for Fig. 12.31:

- LM393 quad comparator IC
- IRF510 MOSFET or equivalent
- 10k-Ω thermistor
- 12-V DC fan, 2 or 3 in. in diameter
- 10k-Ω, ¼-W resistors (2)
- 22k-Ω, ¼-W resistors (2)
- 50-Ω, 5-W resistor

CHAPTER 13

Project 13.1

Sources of microcontrollers:

Adafruit: www.adafruit.com
Arduino: www.arduino.c
Jameco: www.jameco.com
Marlin P. Jones & Associates, www.mpja.com
Mouser: www.mouser.com
Parallax: www.parallax.com
PICAXE: www.pickaxe.com
SparkFun: www.sparkfun.com

Project 13.2

Parts to flash an LED:

- Standard LED
- 470-Ω, ¼-W resistor

Project 13.3

Parts for pushbutton control of an LED:

- Standard LED
- Pushbutton switch with leads to plug into a breadboarding socket
- 470-Ω, ¼-W resistor
- 10k-Ω, ¼-W resistor

CHAPTER 14

Project 14.1

Acquire a soldering iron and some solder. A model with a 20–30W rating with a narrow tip is best. The solder should be 60/40 rosin core. A desoldering tool or braid is an option. Also get basic tools such as wire strippers, needle nose pliers, and side cutters. A knife is also handy.

Project 14.2

- 9-V battery clip and/or four AA cell holder
- #22 solid insulated hook up wire

Project 14.3

Acquire the solder practice kit (SP-1A) or some other kit to practice with.

This page intentionally left blank

Appendix C

Learning Resources

This book provides a good introduction to electronics. But as you will find out, the more you learn the more you realize what you do not know. Most people want to learn more.

Today, most people learn from the Internet. With searches you can find information on almost anything you want to learn. Wikipedia is an example. Listed here are some additional sources that I recommend for your continued learning.

- *All About Circuits* is an online resource for electronic engineers and enthusiasts that offers a wide range of materials including design calculators, articles, textbooks, and projects (http://www.allaboutcircuits.com/tools/).
- *MOOCs* or *Massive Open Online Courses* are online college-level courses covering an extensive array of topics. Many are free; others are low cost. The offerings are extensive so you need to do a search on each website to find what you want. The following are leading providers of MOOCs:
  - Coursera: www.coursera.com
  - EdX: www.edx.com
  - Udemy: www.udemy.com
  - MOOCs listing: www.mooc-list.com
  - MOOCs directory: www.moocs.co
- The *Great Courses* is a source of excellent video courses on DVD, CD, or online. They offer a general electronics course called Understanding Modern Electronics by Professor Richard Wolfson of Middlebury College. Its price varies with discounts offered. Other courses of potential interest are those on science and math (www.thegreatcourses.com).
- EEWeb is a website offering a variety of free electronic tools and calculators. The tools include schematic capture, PCB design and calculations, RF design tools, and passive components calculators. Other features are an online scientific calculator, graph paper and math tools for algebra, trig and calculus (https://www.eeweb.com/toolbox).
- Radio Electronics is a website with an extensive collection of articles and tutorials about all aspects of electronics (www.radio-electronics.com).
- Kahn Academy is a free online learning site offering courses in math, electrical engineering, and programming (www.kahnacademy.com).

This page intentionally left blank

Index

'*Note*: Page numbers followed by "f" indicate figures, "t" indicate tables, and "b" indicate boxes.'

#

3D TV, 278
4G, 3, 197, 212–213
4K, 268–269
5G, 3, 166, 201, 214, 238
555 Timer, 91b–92b, 92f, 96f, 97b, 137f–138f
8K, 269

A

AC. *See* Alternating current
Accumulator
  in ALU, 146
  register, 145–147
Actuator, 303–312. *See also* Motor; Relay; Solenoid
ADC. *See* Analog-to-digital converter
Address buffer, 147–148, 147f
Address bus, 151
Address register, memory, 147–148, 147f
Addressing, in RAM, 126f
Aircraft, radio in, 187
Alkaline battery, 30t
Alternating current (AC), 26–29, 27f
  capacitors' passing of, 51f
  frequency of, 28
  generators for, 33
  inverters for, 33–34
  motor, 311–312
  oscillator in, 26, 34
  polarity of, 26
  signal shapes of, 26–28, 27f
  in solar power system, 88f
  sources for, 33–34
  voltage measurement for, 28–29
Alternator, 33
ALU. *See* Arithmetic logic unit
AM. *See* Amplitude modulation
American Standard Code for Information Interchange (ASCII), 107–112
  character code of, 109t–110t
  control codes of, 108–111
Ampere, 18–19
Amplifier, 7–8, 54–55, 64–65, 71–75
  audio frequency, 65
  BJT, 54f
  cascading, 73–74, 73f
  class A, 66, 67f
  class AB, 66–67
  class B, 66, 67f
  class C, 67–68, 68f
  class D, 68–69, 69f
  class E, 69
  class F, 69
  classification of, 65–71
  configuration of, 65–66
  DC, 64
  differential, 66, 66f, 70f
  efficiency of, 74
  follower, 70f
  frequency response of, 74, 75f
  gain of, 64, 73f
  impedance in, 72–73, 72f
  instrumentation, 70–71, 71f, 297
  intermediate frequency, 65
  inverting and noninverting, 70f
  as linear circuit, 65
  microwave, 65
  operational, 70–71, 70f
  output capability of, 74–75
  power, 65
  pre-, 244
  radio frequency, 65
  in radio receiver, 177
  signal size of, 65
  single-ended, 65, 66f
  switching, 68–69, 69f
  symbol for, 65f
  vacuum-tube, 258b
Amplitude modulation (AM), 170, 171f. *See also* Quadrature amplitude modulation
Amplitude shift key (ASK), 174, 175f
Analog-to-digital converter (ADC)
  for data conversion, 132
  for digital TV, 267f

Analog-to-digital converter (ADC) (*Continued*)
parallel output of, 133f
serial output of, 133f
Antenna, 162, 181–186
dipole, 182, 183f
electromagnetic fields from, 163f
ground-plane, 181, 182f
horn, 185
loop, 183
microwave, 185–186, 185f
patch, 183, 184f
transmission lines to, 183–185, 185f
Yagi, 182–183, 184f
Arduino, 340–341, 341f, 343
Arithmetic circuit, 125
Arithmetic logic unit (ALU), 10, 10f
accumulator in, 146
in computer, 10, 10f, 142
data processing by, 146f
as logic circuit, 125
operation of, 145–147
ASCII. *See* American Standard Code for Information Interchange
ASK. *See* Amplitude shift key
Aspect ratio, 262–263, 264f
Assembly (programming language), 327–328
Astronomy, radio, 191
Asynchronous transfer mode (ATM), 227, 227b
ATM. *See* Asynchronous transfer mode
Atom, 16, 17f
Audio
amplifier, 65
digital, 245–254
dynamic range of, 247b
past recording media, 246–247
electronics, 243
Audio-video receiver (AV receiver), 254–257
diagram of, 255f
radio in, 254–255
Augmented reality (AR), 288
Automatic gain control, 178
AV receiver. *See* Audio-video receiver

B

Band-pass filter (BPF)
bandwidth of, 75–77
response curve of, 76f
symbol for, 76f
Band-reject filter (BRF), 76f
Bandwidth
of BPF, 75–77
modulation and, 172f
of radio, 172, 172f
BASIC (programming language), 328
BASIC Stamp 2, 339
Battery, 29f
cell voltages in, 30t
charging of, 31
as DC source, 29–31
diagram of, 31f
multimeter measurement of, 58f
as power supply, 84
primary cells in, 30–31
secondary cells in, 31
types of, 30t
BCD. *See* Binary-coded decimal
Binary data word, 106
Binary digits, 103–104
Binary numbers, 103–114
decimal conversion from and to, 104–105
hardware representation of, 105
maximum number of states in, 107t
Binary phase shift keying (BPSK), 174, 175f
spectral efficiency of, 209t
Binary-coded decimal (BCD), 107–112
code of, 108t
hexadecimal notation in, 111b
Bipolar junction transistor (BJT), 52–53, 53f–54f
Bits. *See also* Microcontroller; Microprocessor
binary numbers as, 103–114
maximum decimal value calculation for, 106–107
significant, most and least, 104
BJT. *See* Bipolar junction transistor
Bluetooth, 233
Blu-ray DVD, 288
Boat, radio on, 188
Boolean algebraic expressions, 114–115
BPF. *See* Band-pass filter
BPSK. *See* Binary phase shift keying
Breadboard
in home lab, 56b–59b
LED wired on, 59b
socket, 58f
BRF. *See* Band-reject filter
Broadband technology
network with, 237–238
wireless, 238
Bus, 112. *See also* Universal serial bus
address, 151
bidirectional, 151
computer, 151
control, 151
data, 151, 152f
multiplexer, 151
network topology, 220, 221f
parallel data transfer over, 112f

power supply and, 87
sources connected to, 152f
Bus-oriented architecture, 87
Byte, 106

C

C (programming language), 328–329
Cable, 221–222
coax, 221, 222f, 234f
fiber optic, 222, 223f–224f
twisted pair, 221–222, 222f
Cable TV, 278–283
diagram of, 280f, 282f
Internet connectivity with, 237
CAN. *See* Controller area network
Capacitive resistance, 49
Capacitors, 47–50
AC vs. DC with, 51f
charging of, 49f, 60b–61b
construction of, 49f
discharging from, 49f
in LPF, 50f
symbol for, 49f
Carbon, as semiconductor, 20
Cascading amplifier, 73–74, 73f
Cathode ray tube (CRT), 258b
CB. *See* Citizens band
CCD. *See* Charge-coupled device
CD. *See* Compact disc
CDMA. *See* Code division multiple access
Cell. *See also* Battery; Solar cells
fuel, 32–33
load of, 298
photo, 299–302, 299f
symbols for, 299f
Cell phone, 195
4G, 212–213, 212f
CDMA, 202, 211
cellular concept of, 197–199, 198f
communication model of, 8–9, 8f
components of, 199–202
diagram of, 201f
digital modulation in, 203–208
duplex capability of, 199–200
EDGE, 201–202
GPRS, 201–202
GPS in, 216
Cell phone (*Continued*)
GSM, 201–202
hand-off of, 199
HSPA, 202
location technology in, 216
LTE, 202
operation of, 200f
as radio, 195–196
range and reliability of, 196b–197b
smartphone as, 213
spread spectrum in, 175–176
transmission frequency of, 28t
TV on, 285–286
types of, 200–202
Central processing unit (CPU)
components of, 142
control unit of, 142, 147–148
instruction-word formats in, 148–149
program execution in, 149–150
registers in, 144–145
Charge, 16–18
Charge-coupled device (CCD), 270
Chip. *See* Integrated circuit
Circuit, 63. *See also* Digital circuit; Linear circuit; Logic circuit
arithmetic, 125
filter as, 75–77
mixer as, 78–79
model of, 7, 8f, 19f
photo control, 300, 301f
theory of, 41–45
three-state line-driver, 151
Citizens band (CB), 187, 193b
Clock
crystal, 77, 77f
in microprocessor, 154
Coax cable, 221, 222f, 279f
Code. *See also* American Standard Code for Information Interchange; Binary-coded decimal; Decoder
operation, 147–149
for resistors, 48f
Code division multiple access (CDMA)
cell phone use of, 202, 211
generation of, 211f
Codec, 251
Communication. *See also* Duplex communication
cell phone model of, 8–9, 8f
as industry sector, 4, 4f
LOS, 170, 170f
radio system for, 159–160, 160f
with satellite, 189–191, 189f
simplex, 161, 161f
Compact disc (CD), 251–254
dynamic range of, 247b
encoding on, 252f
past recording media vs., 246–247
player, diagram of, 253f

Comparator, 125
Compiler, 326
Components
  capacitors as, 47–50
  of cell phone, 199–202
  of CPU, 142
  diodes as, 52
  in electronics hierarchy, 43f
  IC as, 55–56
  inductors as, 50–51
  as industry sector, 4f, 5
  of microprocessor, 142
  resistors as, 45–46
  switches as, 45, 55, 104
  transformers as, 51–52
  transistors as, 7, 52–55, 104
  types of, 45–56
Compounds, atomic elements in, 16
Compression
  of sound, 248–249
  of video, 271
Computer, 139–142, 143f. *See also* Central processing unit; Memory; Microprocessor
  ALU in, 10, 10f, 142
  applications of, 9
  bus, 151
  control with, 140
  diagram of, 44f
  embedded, 11
  external devices with, 141f
  FFs in, 140
  function of, 9–11
  gates in, 140
  as industry sector, 4, 4f
  input-output system of, 10–11, 10f, 140, 142
  memory of, 142
  as microcontroller, 140
  monitoring by, 141f
  personal, 140
  repairing, 42
  RISC, 155
  sections of, 9–10, 10f
  as system, 43
  types of, 139
Conductor, 20. *See also* Semiconductor
Control. *See also* Industrial control; Microcontroller; Programmable logic controller; Relay
  of actuator, 303–312
  bus, 151
  closed-loop, 291–295, 293f–294f
  computers for, 140
  gain, 178
  as industry sector, 4–5, 4f
  open-loop, 291–295, 292f
  of output device, 303–312
  photo, 300, 301f
  robots as device for, 11
  with thyristor, 312–317
Controller, 294–295. *See also* Microcontroller; Programmable logic controller
Controller area network (CAN), 155b–157b
Copper, atomic composition of, 17f
Core, 140
Coulomb, 18–19
Counter, 121–123
  data conversion with, 123f
  FFs in, 121–122
  program, 147, 147f
CPU. *See* Central processing unit
Crossover, 245, 245f
CRT. *See* Cathode ray tube
Current flow, 7, 16–20. *See also* Alternating current; Direct current
  conventional, 19–20
  direction of, 19–20
  electrons in, 15
  in magnetic fields, 21, 22f
  measurement of, 18–19
  voltage in, 15
Cut-off frequency, 49–50

D

DAC. *See* Digital-to-analog converter
Data
  ALU's processing of, 146f
  bus, 151, 152f
  on fiber optic cable, 224f
  Internet's protocols for, 230f
  LED representation of, 106f
  parallel transmission of, 112–114, 112f
  register's manipulation of, 145f
  retrieval of, 140
  serial transmission of, 112–114
  storage of, 140
  word, binary, 106
Data acquisition system, 321–323
Data conversion, 131–135
  ADC for, 34, 132
  with counter, 123f
  DAC for, 34, 132–133, 134f

resolution in, 133–134
sampling in, 132–134, 132f, 134f
Data processor. *See* Processor
dB. *See* Decibels
DC. *See* Direct current
Decibels (dB), 71
Decimal number system. *See also* Binary-coded decimal; Hexadecimal notation
binary conversion from and to, 104–106
bits' maximum value calculation in, 106–107
Decoder, 124–125, 125f
Demodulator, 179
Demultiplexer, 124
Demux. *See* Demultiplexer
Desoldering, 351–352
Detector. *See* Demodulator
Integrated Development environment (IDE), 327
Diac, 315
Differential amplifier, 66, 66f, 70f
Digital audio, 245–254
Digital circuit, 103–104. *See also* Binary numbers; Data conversion; Gate; Logic circuit; Memory; Programmable logic device
logic elements in, 114–123
Digital compression, 248–250
Digital light processing (DLP), 261–262, 274, 277
Digital modulation
advanced, 203
basic, 174–175, 175f
in cell phone, 203–208
MIMO in, 206–208, 207f
OFDM in, 204–206, 205f–206f, 211
QAM, 203–204, 203f–205f
spectral efficiency of, 208, 209t
Digital radio, 192b, 260b
Digital signal processing (DSP), 157–158, 157f
Digital subscriber line (DSL), 237–238
Digital video disc (DVD), 286–288
Blu-ray, 288
player, 287–288, 287f
Digital video recorder (DVR), 282f
Digital-to-analog converter (DAC), 34, 132–133, 134f
Diode. *See also* Light emitting diode
bias of, 52f
as component, 52
photo, 300f
rectification by, 53f
silicon, 300
symbol for, 52f
temperature sensing with, 297
zener, 52
Dipole antenna, 182, 183f
Direct current (DC), 24–26, 25f, 29–32
amplifier, 65
from batteries, 29–31
capacitors' blocking of, 51f
conversion of, 87, 88f
ground in, 24
motor, 310–311
negative, 26
positive, 24
power supplies for, 33
pulsating, 26
pulse filtering to, 80b
from solar cells, 31–32
in solar power system, 88f
Direct digital synthesis (DDS), 134–135
DIY, do it yourselfer, 3, 89b–90b
Dish, parabolic, 186, 186f
DLP. *See* Digital light processing
Driver
radio amplification with, 177
three-state line, 151
DSL. *See* Digital subscriber line
DSP. *See* Digital signal processing
Duplex communication, 161, 161f
access methods and, 209–211
of cell phone, 199–200
FDD, 209
TDD, 210
Duplexing, 209–211
Duty cycle, 86f, 86b
DVD. *See* Digital video disc
DVR. *See* Digital video recorder
Dynamic range, audio's, 247b

E

Earphones. *See* Headphones, noise-cancelling
EDGE, 201–202
Editor, 327
Effector, end, 11
Efficiency, 74
of amplifiers, 74
spectral, 208, 209t
8051 microcontroller (Intel), 152–154, 153f
Electricity
dynamic, 18–19
electronics vs., 6–7
electrons in, 7, 15–20

Electricity (*Continued*)
as energy source, 15
production of, 15
static, 16–18
Electromagnetic induction, 23–24, 23f
Electromagnetism, 21–23. *See also* Magnetic field; Magnetism
from antenna, 163f
frequency spectrum of, 28t, 164–168, 165f
in radio, 162–164
spectrum space in, 166b–167b
wavelength in, 167b–168b
Electronics
as applied science, 16
audio, 243
concepts in, 15
in daily life, 1
electricity vs., 6–7
hierarchy of, 43f
input-process-output model of, 7–8, 8f
learning about, 2–3
Electronics industry
communications as sector of, 4, 4f
components as sector of, 4f, 5
computers as sector of, 4, 4f
control as sector of, 4–5, 4f
instrumentation as sector of, 4f, 5
manufacturing in, 5–6, 6f
raw materials in, 5, 6f
workings of, 5–7, 6f
Electrons
in atoms, 16
in current flow, 15
in electricity, 7, 15–20
Electrostatic discharge (ESD), 18
Elements, atomic, 16
End effector, 11
ESD. *See* Electrostatic discharge
Ethernet
frame of, 225f
hub, 225f
networking with, 223–225
operation of, 225–226

F

Fast Fourier transform (FFT), 158
FCC. *See* Federal Communications Commission
FDD. *See* Frequency-division duplexing
FDMA. *See* Frequency division multiple access
Federal Communications Commission (FCC), 164
Feedback, in closed-loop control, 293f
FF. *See* Flip-flop
FFT. *See* Fast Fourier transform
Fiber optic cable, 222, 223f
data transmission over, 224f
TV over, 281b
Filter. *See also* Band-pass filter; Band-reject filter; High-pass filter; Low-pass filter
as circuit, 75–77
pulse to DC, 80b
surface acoustic wave, 77
Flag, 148
Flag register, 148
Flip-flop (FF), 119–120
cascading, 120f
in computer, 140
in counters, 121–122
in storage register, 121f
symbols for, 119f
FM. *See* Frequency modulation
Fourier theory, 34–35. *See also* Fast Fourier transform
harmonics and, 68
Frequency. *See also* Amplifier
of AC, 28
of cell phone transmission, 28t
cut-off, 49–50
domain, 34–35, 35f
of electromagnetic spectrum, 28t, 164–168, 165f
Fourier theory and, 34–35
intermediate, 274
of oscillators, 77–78
of radar transmission, 28t
of satellite transmission, 28t
synthesizers, 82–83, 83f
of TV transmission, 28t
Frequency division multiple access (FDMA), 209
Frequency modulation (FM), 173–174, 173f
sidebands on, 173–174
Frequency shift keying (FSK), 174, 175f
spectral efficiency of, 209t
Frequency-division duplexing (FDD), 209
FSK. *See* Frequency shift keying
Fuel cell, 32–33
Function generators, 34

G

Gain
of amplifier, 65, 73f
control, 178
dB for measurement of, 71

power, 71
voltage, 71
GAL. *See* Generic array logic
Gate
AND, 115–116, 115f–116f
OR, 117, 117f
in computer, 140
NAND, 117–118, 118f
NOR, 117–118, 118f
XNOR, 119f
XOR, 118, 119f
Gateway, 239–240
Gauge, strain, 297, 298f
Gaussian minimum shift keying, 201–202
General Packet Radio System (GPRS), 201–202
General-purpose register (GPR), 144
Generator
AC, 33
function, 34
Generic array logic (GAL), 129
Germanium, 20
Global positioning system (GPS), 190
in cell phones, 216
Global System for Mobile Communications (GSM), 201–202
GPR. *See* General-purpose register
GPRS. *See* General Packet Radio System
GPS. *See* Global positioning system
Ground, 50b
in DC, 24
symbol for, 51f
Ground-plane antenna, 181, 182f
Groupe Spécial Mobile. *See* Global System for Mobile Communications
GSM. *See* Global System for Mobile Communications

H

Ham radio, 188
HAN. *See* Home area network
Hard copy, 144
Hardware
binary numbers represented by, 105
purchasing, 36b
of radio, 176–181
Harmonics, 68
HDMI. *See* High-definition media interface
Headphones, noise-cancelling, 258–259
Hearing
aids, 259–260
testing of, 260b
Hertz (Hz), 26
Hexadecimal notation, 111b
High frequency radio, 169
High-definition media interface (HDMI), 274
High-definition TV (HDTV), 43, 254
packet in, 272f
resolution of, 268
High-pass filter (HPF), 76f
High-speed packet access (HSPA), 202
Home area network, 219
Home entertainment system
satellite TV in, 284f
as system, 43
Horn antenna, 185
HPF. *See* High-pass filter
HSPA. *See* High-speed packet access
Hydraulic device, 312
Hydrophone, 259
Hz. *See* Hertz

I

IC. *See* Integrated circuit
IDE. *See* Integrated Development Environment
Impedance, 72b
in amplifier, 72f, 73–74
input, 72–73
output, 73
Induction
electromagnetic, 23–24, 23f
self-, 50–51
Inductive reactance, 50–51
Inductors, 50–51, 51f
Industrial, scientific, and medical band (ISM band)
applications of, 235
project on, 192b
transceiver, 179–181
Industrial control, 291
actuator in, 303–312
closed-loop, 291–295, 293f–294f
controllers in, 294–295
diagram of, 292f
motor in, 310
open-loop, 291–295, 292f
output device in, 303–312
relay in, 305
sensors in, 295–302
solenoid in, 309, 309f
with thyristor, 312–317
Instruction register (IR), 147
Instruction-word formats, 148–149, 149f
Instrumentation, as industry sector, 4f, 5

Instrumentation amplifier, 70–71, 71f, 297
Instruments, musical, 257–258
Insulators, 20
Integrated circuit (IC), 2, 55–56
  transistors in, 7
Integrated Development Environment
Interface, 144
  high-definition media, 274
  to microcontroller, 155b–157b
  serial peripheral, 155b–157b
International Telecommunications Union (ITU), 164
Internet, 228–229
  on cable TV, 237
  diagram of, 228f
  protocols used on, 230f
Internet of Things (IoT), 230–231, 238–242, 240f
Interrupt, 154
Inversion, 114
  in amplifiers, 70f
  phase, 54–55
Inverters
  in AC, 33–34
  logic of, 114–115
  as power supply, 87
  symbols for, 114f
IPTV. *See* Internet protocol TV
IR. *See* Instruction register
ISM band. *See* Industrial, scientific, and medical band
ITU. *See* International Telecommunications Union

K

Kit building, 88b–89b

L

Lab, set up of, 56b–59b
LAN. *See* Local area network
Language. *See* Programming language
LaunchPad, 341, 342f, 343
LCD. *See* Liquid crystal display
Lead acid battery, 30t
LED. *See* Light emitting diode
Light
  photo control circuit for, 300, 301f
  speed of, 164
Light emitting diode (LED), 52
  binary data represented by, 106f
  on breadboard, 59b
  MOSFET switching of, 61b
  OLED, 277, 278b
Lightning, 17–18
Linear circuit, 63–100
  amplifier as, 65
  filter as, 75–77
  mixer as, 78
  phase detector as, 79
  straight-line response of, 64f
Line-of-sight communication (LOS communication), 170, 170f
Liquid crystal display (LCD)
  operation of, 143
  TVs made with, 261–262
Lithium ion battery, 30t
Local area network (LAN), 218
Logic. *See also* Gate; Programmable logic controller
  Boolean, 114–115
  digital, 114–123
  generic array, 129
  of inverter, 114–115
  ladder, 320, 321f
  in PAL, 129
  in PLA, 129
  in PLD, 129–131, 130f
Logic circuit, 124–125
  ALU as, 125
  comparator as, 125
  decoder as, 124–125, 125f
  demultiplexer as, 124
  multiplexer as, 124, 124f
Logic gate. *See* Gate
Long-Term Evolution (LTE), 202
Loop antenna, 183
LOS communication. *See* Line-of-sight communication
Low frequency radio, 168
Low-pass filter (LPF)
  capacitors in, 50f
  function of, 75
  in PLL, 80
  response curve of, 76f
  symbol for, 76f
LPF. *See* Low-pass filter
LTE. *See* Long-Term Evolution

M

Machine-to-Machine (M2M), 214, 230–231, 239–240
Magazines, 37b
Magnetic field, 20–21, 21f
  current flow in, 21, 22f
  voltage induction with, 23f

Magnetic tape, 246
Magnetism, 20–24
  attraction and repulsion in, 21
  flux lines in, 21f
  magnetic fields in, 20–21, 21f
  materials exhibiting, 20
Maker, 3, 347
MAN. *See* Metropolitan area network
Manipulator arm, robot's, 11, 12f
Manufacturing, electronics industry, 5–7, 6f
Marine radio, 188–189
Memory. *See also* Random access memory; Read-only memory
  in computer, 142
Memory address register, 147–148, 147f
Mercuric oxide battery, 30t
Mesh network topology, 219–220, 234f
Metal oxide semiconductor-field-effect transistor (MOSFET), 53, 54f
  in class C amplifier, 67–68
  LED switching by, 61b
  switch, 55f
Metropolitan area network (MAN), 218
Microcomputer. *See* Computer
Microcontroller, 11
  8-bit, 152–154
  16-bit, 152–154
  32-bit, 155–157
  64-bit, 155–157
  computer as, 140
  8051 (Intel), 152–154, 153f
  interfaces to, 155b–157b
  MPS430 (Texas Instruments), 154
Microphone, 244
Microprocessing unit. *See* Central processing unit; Microprocessor
Microprocessor, 140. *See also* Central processing unit
  8-bit, 152–154
  16-bit, 152–154
  32-bit, 155–157
  64-bit, 155–157
  clock in, 154
  components of, 142
  instruction-word formats in, 148–149
  popular, 151–157
  RISC, 155
Microwave
  amplifier, 65
  antenna, 185–186, 185f
  propagation of, 169
  radio, 169–170
MIMO. *See* Multiple input multiple output
Mixer, 78–79
  as circuit, 78
  linear, 78, 79f
  nonlinear, 78–79, 79f
  outputs, 78–79
  in radio receiver, 178
Mobile telephone switching office, 199
Modulation, 170–176. *See also* Amplitude modulation; Digital modulation; Frequency modulation; Quadrature amplitude modulation
  angle, 174
  ASK in, 174
  bandwidth and, 172f
  demodulator and, 178
  OOK in, 174
  phase, 174
  pulse width, 68–69, 86b
  sidebands from, 171–172
MOSFET. *See* Metal oxide semiconductor-field-effect transistor
Motor
  AC, 311–312
  applications of, 310
  DC, 310–311
  industrial control with, 310b
  speed regulation of, 295f
  stepper, 311
MP3 player
  diagram of, 44f, 250f
  operation of, 250–251
  as system, 43
MPS430 microcontroller (Texas Instruments), 154
Multimeter, 35b–36b
  battery measurement with, 58f
Multiple input multiple output (MIMO)
  in digital modulation, 206–208, 207f
  spectral efficiency of, 209t
Multiplexer. *See also* Demultiplexer
  bus, 151
  as logic circuit, 124, 124f
Multiplexing, 209–211. *See also* Orthogonal frequency division multiplexing
Musical instruments, 257–258
Mux. *See* Multiplexer

N

Network, 217–218
  Bluetooth, 233
  with broadband technology, 236–238
  CAN as, 155b–157b

Network (*Continued*)
DSL for, 237–238
with Ethernet, 223–225
HAN as, 219
interconnection methods for, 219–220, 220f
LAN as, 218
MAN as, 218
near-field, 235–236
PAN as, 218–219
relationships of, 219
RFID as, 235–236, 236f
SAN as, 219
with Sonet, 226–228, 226t
topologies of, 219–220, 220f, 234f
types of, 218–219
WAN as, 218
Wi-Fi, 231–233
wired, 220–228
wireless, 230–236, 231f
ZigBee, 233–234
Nibble, 106
Nickel metal hydride battery, 30t
Nickel-cadmium battery, 30t
Noise, in radio, 160b
Noise-cancelling headphones, 258–259

O

Octet, 106
OFDM. *See* Orthogonal frequency division multiplexing
Ohm's law, 46b
On-off keying (OOK), 174, 175f
OOK. *See* On-off keying
Operating system (OS), 326–327
Operation code, 147, 149f
Orthogonal frequency division multiplexing (OFDM)
digital modulation with, 204–206, 205f–206f, 211
spectral efficiency of, 209t
OS. *See* Operating system
Oscillator, 77–78. *See also* Clock; Voltage-controlled oscillator
in AC, 26, 34
frequency of, 77–78
types of, 77f
OTN. *See* Optical transport network
OTT. *See* Over the Top TV
Optical transport network, 228
Over the Top TV (OTT), 285

P

PAL. *See* Programmable array logic
PAN. *See* Personal area network
Parabolic dish, 186, 186f
Patch antenna, 183, 184f
PCB. *See* Printed circuit board
Peripherals, 144. *See also* Serial peripheral interface
Personal area network (PAN), 218–219
Phase detector, 79–80, 80f
as circuit, 79–80
Phase inversion, 54–55
Phase modulation, 174
Phase shift keying (PSK), 174, 175f
Phase-locked loop (PLL), 80–82
divide ratio of, 84t
in frequency synthesizers, 82–83, 83f
LPF in, 80
VCO in, 80–82
Phonograph record, 246, 247b
Photo cell, 299–302, 299f
Photodiode, 300f
Photoelectric sensor, 299–302
Phototransistor, 299f, 300, 302f
Photovoltaic (PV), 31–32, 299
PIC processor (Microchip Technology), 154
PICAXE, 339–340
Piezoelectric pressure transducer, 298
Pixel, 266, 267f, 277f, 289b
PLA. *See* Programmable logic array
Plasma screen
operation of, 143
TVs made with, 261–262
PLC. *See* Programmable logic controller
PLD. *See* Programmable logic device
PLL. *See* Phase-locked loop
Pneumatic device, 312
Polarization, radio, 163b
Potential, 162
Potentiometer, 298
Power amplifier, 65
Power gain, 71
Power supply, 84–100
battery as, 84
bus-oriented architecture in, 87
for DC, 33
DC-DC converters in, 87
inverters as, 87
power management in, 87
regulators in, 85–86
solar, DC-to-AC, 88f
standard, 84–85, 85f

PowerPC (Freescale), 155
Preamplifier, 244
Printed circuit board (PCB)
  in kit, 88b–89b
  patch antenna on, 184f
  soldering, 347, 351, 351f
Processor, 140. *See also* Central processing unit; Microprocessor
Program
  counter, 147, 147f
  CPU's execution of, 149–150
  in RAM, 150f
  storage concept for, 150
Programmable array logic (PAL), 129
Programmable logic array (PLA), 129
Programmable logic controller (PLC), 318–323
  diagram of, 318f
  operation of, 319–320
  organization of, 318–319
  programming of, 320–321
  scan cycle of, 319f
Programmable logic device (PLD), 129–131, 130f
Programming language, 326–329
  assembly, 327–328
  BASIC, 328
  C, 328–329
  with PLC, 320–321
PSK. *See* Phase shift keying
Pulse filter into DC, 80b
Pulse width modulation (PWM), 68–69
  duty cycle and, 85
PV. *See* Photovoltaic
PWM. *See* Pulse width modulation

R

Radar
  project, 193b
  transmission frequency of, 28t
Radio, 162. *See also* Duplex communication; Modulation; Sidebands
  in aircraft, 187
  AM, 171, 171f
  AV receiver with, 254
  bandwidth of, 172, 172f
  CB, 187, 193b
  cell phone as, 196
  communication system, 159–160, 160f
  digital, 192b, 260b
  driver for, 177
  electromagnetic field as, 162–164
  family, 188
  frequency amplifier, 65
  frequency types, 28t, 168–170
  GPRS, 201–202
  ham, 188
  hardware of, 176–181
  LOS communication with, 170, 170f
  marine, 188–189
  microwave, 169–170
  mobile, 189
  modes of, 160–161
  multipath transmission of, 196b–197b
  noise in, 160b
  polarization of, 163b
  propagation of, 168–170
  range and reliability of, 196b–197b
  receiver, 177–179, 178f
  shortwave, 169f
  signal speed and strength of, 164
  simplex, 161, 161f
  spread spectrum in, 175–176
  transceiver, 179
  transmission lines in, 183–185, 185f
  transmitter, 176–177, 177f
  two-way, 186–189
Radio astronomy, 191
Radio frequency identification (RFID), 235–236, 236f
Radio telescope, 191
RAM. *See* Random access memory
Random access memory (RAM), 126–128
  addressing in, 126f
  dynamic, 127, 127f
  program stored in, 150f
  static, 126–127, 127f
Raspberry Pi, 341–342
Reactance, inductive, 50–51
Read-only memory (ROM), 128–129
Receiver. *See also* Audio-video receiver
  radio, 177–179, 178f
  satellite TV, 285f
  superheterodyne, 178f
  TV, 274
Recommended Standard 232 (RS-232), 155b–157b, 156f
Recommended Standard 485 (RS-485), 155b–157b
Record, phonograph, 246, 247b
Reduced instruction set computer (RISC), 155
Reed relay, 305, 305f
Register
  accumulator, 145
  in CPU, 143, 145
  data manipulation in, 145f
  flag, 148

Register (*Continued*)
general-purpose, 144
instruction, 147
memory address, 147–148, 147f
operation of, 145–151
shift, 121, 122f
stack pointer, 148
storage, 120, 121f
Regulator
linear, 85
in power supplies, 86b
switching, 85
Relay, 303–309
common contacts of, 304f
current control with, 305–306
diagram of, 303f
industrial control with, 305
latching of, 307, 308f
reed, 305, 305f
remote control with, 306
as switch, 303–304
transistor with, 308f
Resistance, capacitive, 49
Resistive sensor, 296f
Resistive temperature device (RTD), 296, 296f
Resistors, 45–46
color codes for, 48f
symbol for, 47f
types of, 47f
in voltage divider, 48f
Resolution
in data conversion, 133–134
of HDTV, 268
of video, 269
RFID. *See* Radio frequency identification
Ring network topology, 220, 221f
RISC. *See* Reduced instruction set computer
Robots, 11
building of, 322b
as control device, 11
end effectors of, 11
manipulator arm of, 11, 12f
ROM. *See* Read-only memory
Routers, 229
RS-232. *See* Recommended Standard 232
RS-485. *See* Recommended Standard 485
RTD. *See* Resistive temperature device

S

Sampling
in data conversion, 132–134, 132f, 134f
sound, 249f
SAN. *See* Storage area network
Satellite
communication, 189f, 190
geosynchronous orbit of, 190
transmission frequency of, 28t
transponder of, 190f
Satellite TV, 283–285
distribution system for, 283f
in home entertainment system, 284f
receiver diagram with, 285f
SAW. *See* Surface acoustic wave
Scanning, 262, 263f
interlaced, 265f
progressive, 268
SCR. *See* Silicon-controlled rectifier
Self-induction, 50–51
Semiconductor, 20. *See also* Metal oxide semiconductor-field-effect transistor; Thyristor
carbon as, 20
germanium as, 20
silicon as, 20
Sensor
of flow, 302
in industrial control, 295–302
photoelectric, 299–302
potentiometer as, 298
pressure, 297–298
resistive, 296f
switch as, 298
of temperature, 296–297
Serial peripheral interface (SPI), 155b–157b
Shift key, 174, 175f. *See also* Quadrature amplitude modulation
with ASK, 174, 175f
with BPSK, 174, 175f, 209t
with FSK, 174, 175f, 209t
with Gaussian minimum, 201–202
with OOK, 174, 175f
with PSK, 174, 175f
Shift register, 121, 122f
Sidebands
on FM, 173–174
from modulation, 171–172
vestigial, 272–273
Signal, 7. *See also* Digital signal processing
in AC, 26, 27f
from amplifier, 65
analog, 34, 63–64
binary, 26, 103, 104f
digital, 26, 34
distortion of, 66–67
radio, 164

Silicon
  diode made of, 300
  as semiconductor, 20
Silicon-controlled rectifier (SCR), 312–315, 313f–314f
Silver oxide battery, 30t
Simplex communication, 161, 161f
Smartphone, 195–196, 211–213, 215–216
SoC. *See* System on a chip
Software, 325–329
Solar cells
  as DC source, 31–32
  in panel, 32f
  symbol for, 299f
Solar power system, DC-to-AC, 88f
Solder, 347–348, 353b
Soldering, 347, 349–351, 350f–351f, 352b
Soldering iron, 347–348, 348f
Solenoid, 309, 309f
Sonar, 259
Sonet. *See* Synchronous optical network
Sound, 243–245
  compression of, 248–249
  digitization of, 247–248, 248f
  frequency of, 28t
  sampling of, 249f
  in special applications, 257–260
  surround, 256–257, 256f
Speakers, 244–245
  diagram of, 244f
  surround sound with, 256–257, 256f
  as transducer, 244
  types of, 245
Spectral efficiency, 208, 209t
Spectrum
  electromagnetic frequency, 28t, 164–168, 165f
  space, 166b–167b
  spread, 175–176
SPI. *See* Serial peripheral interface
Spread spectrum, 175–176
Stack, 148
Stack pointer register, 148
Star network topology, 17, 19f
Static electricity, 16–18
Stepper motor, 311
Storage area network (SAN), 219
Storage register, 120
  FFs in, 121f
Stored program concept, 150
Strain gauge, 297, 298f
Streaming audio, 257
Subroutines, 327
Surface acoustic wave (SAW), 77
Surround sound, 256–257, 256f
Switch, 45
  as component, 42–43, 45, 55
  limit, 298
  MOSFET, 55f
  relay as, 303–309
  schematic of, 45
  as sensor, 298
Switching
  amplifier, 68–69, 68f
  of LED, 61b
  mobile telephone, 199
  regulator, 85–86
  transistor, 55
Synchronous digital hierarchy. *See* Synchronous optical network
Synchronous optical network (Sonet), 226–228
Synthesizer, frequency, 82–83, 83f
System on a chip (SoC), 63
Systems approach, 1, 41–45

T

Tachometer, phototransistor in, 302f
TDD. *See* Time-division duplexing
TDMA. *See* Time division multiple access
Telephone, mobile switching of, 199
Telephone data system, 227b
  ATM in, 227b
Television (TV). *See also* Cable TV; High-definition TV; Internet protocol TV; Satellite TV
  ADC for, 267f
  analog, 264–266
  aspect ratio of, 262–263, 264f
  on cell phone, 285–286
  diagram of, set, 119f
  digital, 266–269
  frequency of, 28t
  inputs and outputs of, set, 119f
  international systems for, 266b
  over fiber optic cable, 281b
  with plasma screen, 274
  receiver, 274
  screen technology of, 274–276, 277f
  transmission of, 272–274, 273f
Temperature sensor, 296–297
Thermistor, 296
Thermocouple, 296
Thyristor
  control with, 312–317
  diac, 315
  SCR, 312–315, 313f–314f
  triac, 315–317, 315f

Time division multiple access (TDMA), 209–210, 210f
Time-division duplexing (TDD), 210
Timer, 154
Transceiver
  ISM band, 179–181
  radio, 179
  single-chip, 180f
Transducer
  piezoelectric pressure, 298
  speaker as, 244–245
Transformer, 51–52, 51f
Transistor, 52–55. *See also* Metal oxide semiconductor-field-effect transistor
  bipolar junction, 52–53, 53f–54f
  as component, 7, 52–55, 104
  IC in, 7
  photo-, 299f, 300, 302f
  relay with, 308f
  switching, 55
  symbols for, 53f
  temperature sensing with, 297
  types of, 52–53
Transmitter
  radio, 176–177, 177f
  TV, 272f
  UART as, 155b–157b, 156f
Transponder, satellite, 190f
Triac, 315–317, 317f
Truth table, 115
  for AND gate, 115f
  for OR gate, 117f
  inverter for, 114f
  for NAND gate, 118f
  for NOR gate, 118f
  for XNOR gate, 119f
  for XOR gate, 119f
TV. *See* Television
Twisted pair cable, 221–222, 222f

U

UART. *See* Universal asynchronous receiver-transmitter
Ultra high frequency radio, 169–170
Universal asynchronous receiver-transmitter (UART), 155b–157b, 156f
Universal serial bus (USB), 155b–157b
USB. *See* Universal serial bus

V

Vacuum tubes, 258b
Valve, 312
Varactor, 52
VCO. *See* Voltage-controlled oscillator
Very high frequency radio, 169–170
Video, 261–277
  aspect ratio of, 262–263, 264f
  CCD for, 270
  color, 269–270, 269f–270f
  compression of, 271
  monochrome, 269
  persistence of vision in, 263–264
  resolution of, 268b
  scanning in, 262, 263f, 265f, 266, 268
Virtual reality (VR), 288
Vision, persistence of, 263–264
Voice
  coil, 244–245
  sampling of, 249f
Voltage, 3–5, 7
  of AC, 28–29
  of battery cell, 30t
  in current flow, 15
  divider, 48f
  as electrical potential difference, 17
  gain, 71
  induction of, 23f
  measurement of, 37b–38b
  sources of, 24–29
Voltage-controlled oscillator (VCO), 77–78, 77f
  in PLL, 80–82

W

WAN. *See* Wide area networks
Wave. *See also* Microwave
  short, 169f
  surface acoustic, 77
Waveguide, 185–186
Wavelength, in electromagnetism, 167b–168b
Wide area networks (WAN), 218
Wi-Fi, 231–233
Wireless, 147. *See also* Radio
  broadband, 238
  networks, 230–236, 231f
  trend in, 227b
Word
  binary data, 106
  instruction, 148–149, 149f

Y

Yagi antenna, 182–183, 184f

Z

ZigBee, 233–234

Electronic Engineering

ELECTRONICS EXPLAINED

Fundamentals for Engineers, Technicians, and Makers

Second Edition

Louis E. Frenzel Jr.

Take a fresh, systems based approach to understanding how electronics work!

Electronics Explained takes a systems based approach to the fundamentals of electronics, covering the different types of electronic circuits, how they work, and how they fit together to create modern electronic equipment, enabling you to apply, use, select, operate and discuss common electronic products and systems.

This new edition has been updated to show the latest technological trends with added coverage of:

- Internet of Things (IoT)
- Machine-to-Machine (M2M) technology
- Ethernet to 100 Gb/s
- Wi-Fi, Bluetooth, and other wireless technologies
- 5G New Radio cellular standards
- Microcontrollers and programming with the Arduino, BASIC Stamp, and others

With this book you will:

- Learn about the basic components of electronics such as resistors, capacitors, inductors, transformers, diodes, transistors, and integrated circuits.
- Discover different types of circuits, using the functional block diagram approach which makes it easy to understand their purpose and application.
- Get involved with Hands-On projects in each chapter, using components and ICs with the breadboarding socket.

About the author

Louis E. Frenzel Jr. has been a Technology Editor with Electronic Design magazine since 2000 and covers the wireless, communications, and networking and test/measurement fields Lou has over 30 years of electronic industry experience as an engineer in the geophysical, aerospace and computer fields. Prior to joining ED he was a college professor teaching electronics and semiconductor manufacturing and working on several NSF grants. He holds bachelors and masters degrees and is author of 21 books on communications, computers and electronics.

Cover image © iStockphoto

ISBN 978-0-12-811641-8

ELSEVIER

Newnes
An imprint of Elsevier
elsevier.com/books-and-journals

If you enjoyed this book please post a review to your favorite online bookstore today.